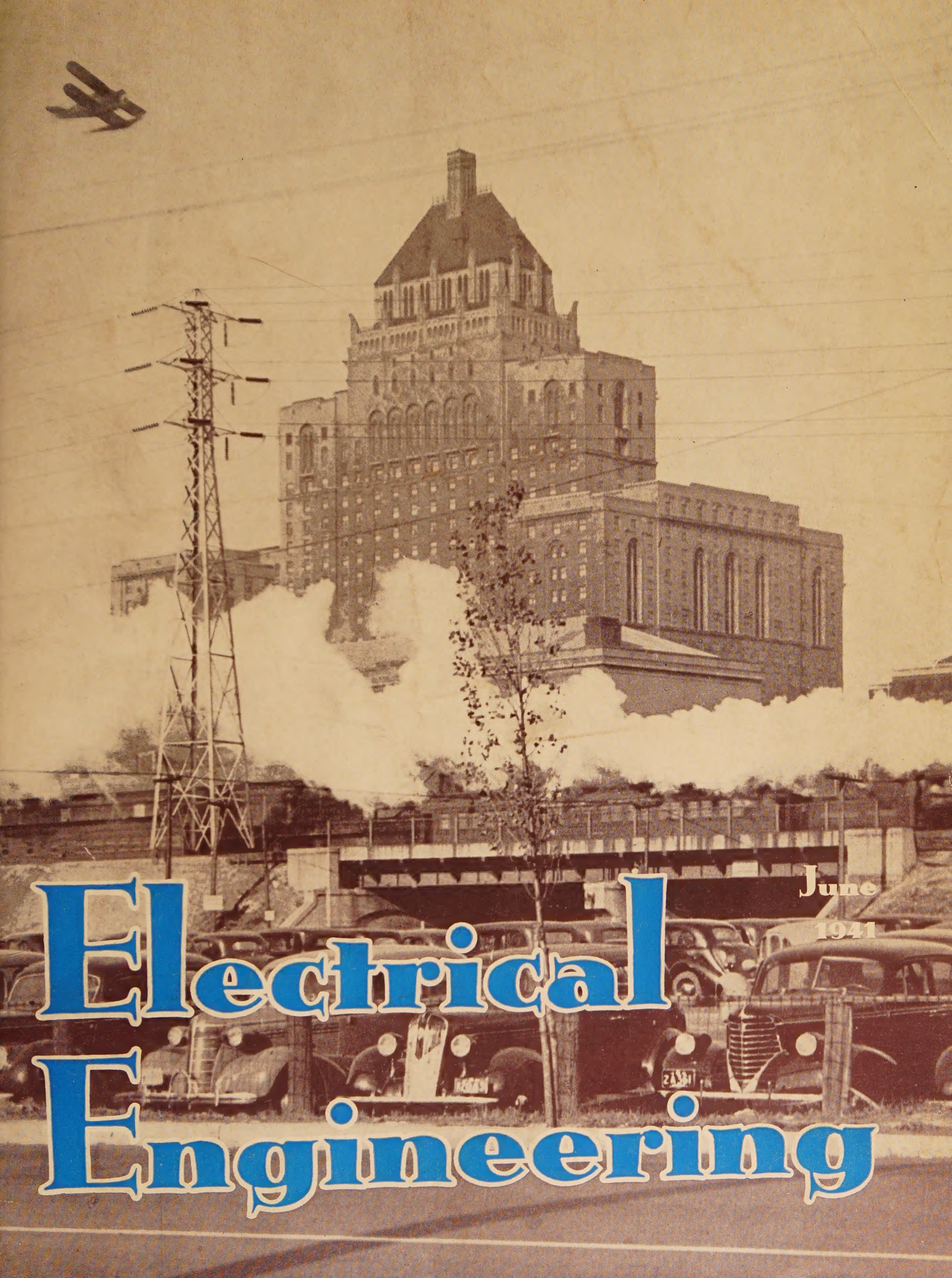
AIEE Summer Convention, Toronto, Ontario, Canada, June 16–20, 1941



Electrical Engineering

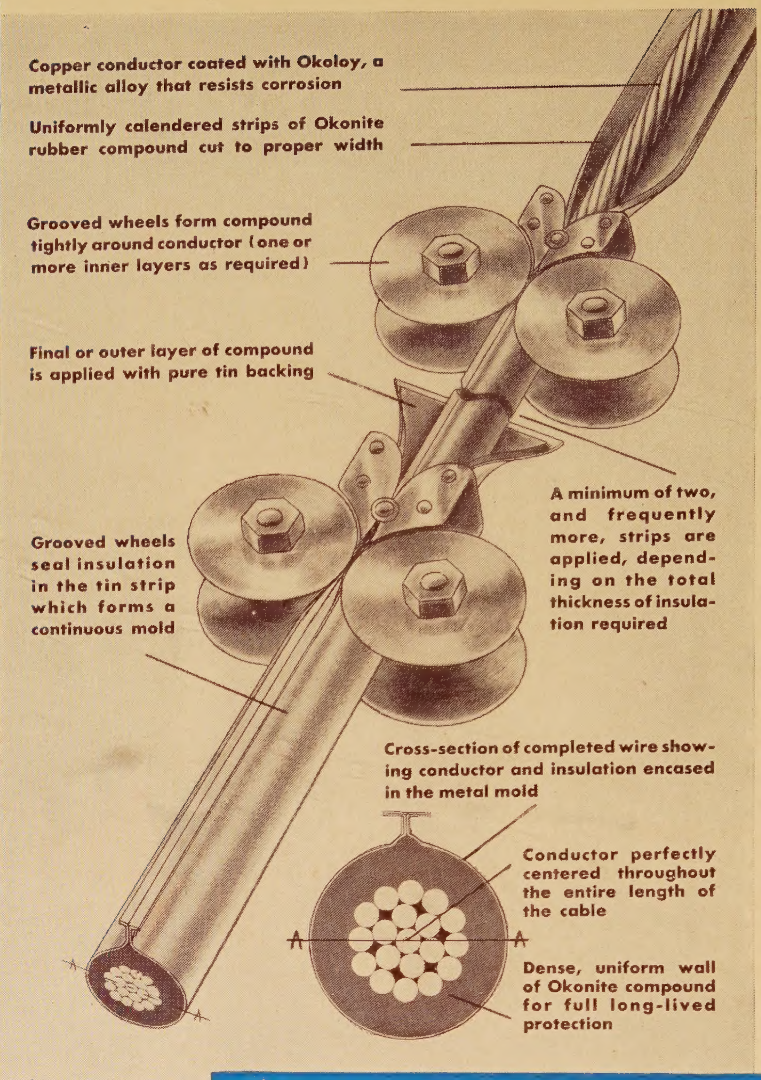
June 1941

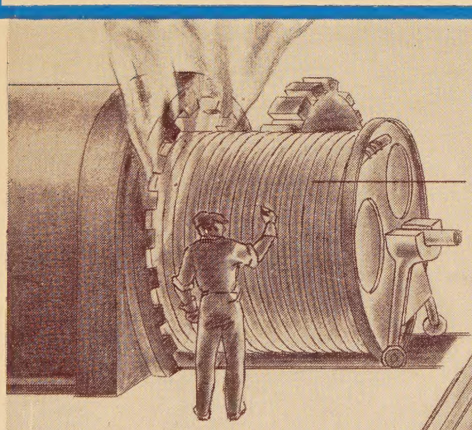
OKONITE

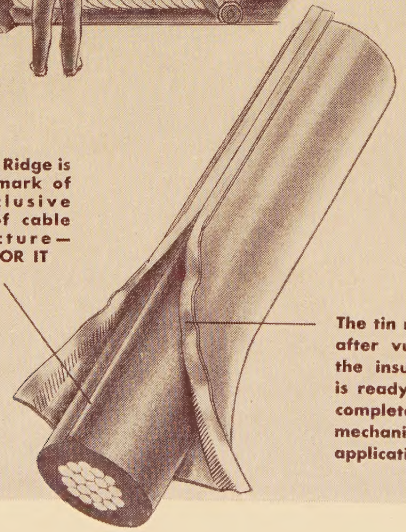
Insulation is Applied by This EXCLUSIVE PROCESS

Okonite wires and cables have always been distinguished for long life, exceptional electrical characteristics, high insulation density and perfect centering of conductors.

Of utmost importance to the attainment of these results is Okonite's strip-insulating process by which the insulation is wrapped around the conductor and sealed in a continuous metal mold during vulcanization. For nearly 60 years we have made Okonite insulation this way and for 60 years Okonite has been compiling unequalled records for unfailing performance under severest service conditions.







5 FOUNDATIONS OF OKONITE QUALITY

1. Made only with Up-river Fine Para rubber carefully washed and dried
2. The Okonite formula is proved by long use rather than accelerated tests
3. Conductors perfectly centered by the Okonite strip-insulating process
4. Uniformly vulcanized under pressure in a continuous metal mold
5. Thoroughly tested and inspected throughout the manufacturing process

Okonite's Okoloy coating on conductors eliminates corrosion

THE OKONITE COMPANY
Passaic, New Jersey
Offices in principal cities

OKONITE OKONITE **Insulated Wires and Cables**

Electrical Engineering

Registered U. S. Patent Office

for June 1941—

The Cover: The Royal York Hotel, Toronto, Ontario, Canada, headquarters for the AIEE 1941 summer convention, June 16–20, towers above its surroundings
Photo by J. H. Mackay, Hydro-Electric Power Commission of Ontario

Transactions Section *(Follows EE page 310; a preprint of pages 249–312 of the 1941 volume)*

©

VOLUME 60 FOUNDED 1884 NUMBER 6

A Monthly Publication of

American Institute of Electrical Engineers

33 West Thirty-Ninth Street, New York, N. Y.

ROYAL W. SORENSEN, President H. H. HENLINE, National Secretary

——PUBLICATION COMMITTEE——

D. M. Simmons, *chairman* J. W. Barker O. W. Eshbach H. H. Henline H. W. Hitchcock S. H. Mortensen A. G. Oehler H. S. Phelps H. H. Race S. P. Shackleton M. W. Smith I. Melville Stein S. B. Williams

——PUBLICATION STAFF——

G. Ross Henninger, Editor
Floyd A. Lewis, Associate Editor
F. A. Norris, Business Manager
C. A. Graef, Advertising Manager

¶ Statements and opinions given in articles and papers appearing in "Electrical Engineering" are the expressions of contributors, for which the Institute assumes no responsibility.

¶ Correspondence is invited on all controversial matters.

High Lights • •

Engineers and National Defense. For the past two months ELECTRICAL ENGINEERING has carried news items on Defense thought to be of especial interest to engineers, and particularly to electrical engineers. In this issue may be found a third group of current items on this subject (*pages 302–05*). Among these, especial attention is called to one which outlines the efforts being made to keep engineers out of routine military service and retain them where their training and experience will enable them to make their greatest contribution to the National Defense program as a whole (*pages 302–03*). This subject, which is of such great import at this time of accelerated industrial production, is discussed further in: (1) an article advocating a system of "priorities in men" parallel to the system of priorities in materials (*pages 247–50*); (2) President R. W. Sorensen's current message to the AIEE membership (*page 280*); and (3) a "Letter to the Editor" (*page 309*).

Fluorescent Lighting. Introduced commercially only a few years ago, fluorescent lighting already has advanced to a prominent position in the lighting art. Although many of the earlier applications of this new lighting tool were crude and therefore somewhat unsatisfactory, correct methods of application are being developed, with greatly improved installations as a result. These are some of the points brought out at a conference on the subject held during the AIEE 1941 winter convention. Four of the scheduled informal discussions, on low-voltage equipment and installations, are included in this issue (*pages 261–70*); a fifth, outlining progress in high-voltage fluorescent tubing, is scheduled for an early issue.

Bushings. Studies of porcelain oil-filled bushings have resulted in better understanding of the internal and external electrostatic field condition, and in the development of a new method of voltage grading (*Transactions pages 255–60*). Proposed electrical requirements for indoor and outdoor apparatus bushings rated 2,500 volts and higher have been tabulated by the AIEE joint committee on bushings (*Transactions page 266*).

Suppressing Magnetic Vibration. An investigation of the double-frequency vibration of two-pole generators caused by distortion of the stator by magnetic forces resulted in two methods for reducing this vibration: stiffening the stator core, and providing a resilient core-mounting to isolate the vibration (*Transactions pages 283–8*).

Calculating Fault Currents. With industry expanding at its present accelerated rate, a knowledge of fault currents in the electrical systems becomes increasingly important; a method of calculating these fault currents, with an example illustrating in detail how it may be applied, is presented in this issue (*pages 271–9*).

Local Institute Activities. The annual report on AIEE Section and Branch activities for the fiscal year shows organization of two new Sections and three new Student Branches; two former Branches were combined into one when the schools were consolidated. Sections now total 72; Branches 123 (*pages 285–7*).

Construction Theorem. A direct method has been evolved for evaluating operational expressions involving a finite number of different roots; in order that it may be of value to engineers unfamiliar with integration in the complex plane, no mathematically rigorous proof is included (*Transactions pages 273–6*).

Ignitron Arc-Backs. Experiments have been carried out to test the theory that the arc-back rate of ignitrons operating in series should be very low in comparison with the arc-back rate of the individual ignitron operating alone on its share of the voltage; results of the tests are reported (*Transactions pages 292–4*).

Enclosed Bus-Bar Distribution Systems. The enclosed bus-bar type of low-voltage electrical-distribution system for industrial plants, an outgrowth of the mass-production methods of the automotive industry, has met the needs of a variety of public and industrial buildings; its characteristics are discussed (*Transactions pages 297–302*).

Atom Smashing. The principles of atomic structure and atomic transmutation were reviewed, several types of "atom-smashers" described, and some applications of the method of "tracer" atoms to medical problems outlined in an address presented at the AIEE 1941 winter convention (*pages 250–60*).

Transformer Sound Levels. Investigations have shown the basic source of sound in transformers to be the magnetostriction of the magnetic sheet steel; a method of calculating sound levels has been found which gives results in close agreement with measured values (*Transactions pages 277–83*).

High-Potential Testing. An attempt has been made to evaluate the damaging effect on an insulation system of the surge voltages encountered in the rapid production testing of the dielectric strength of low-voltage apparatus (*Transactions pages 289–92*).

Testing by Power Factor. The power-factor method of testing bushing and associated insulation has been used as a maintenance tool in the field and the reconditioning shop; conclusions from eight years' experience are presented (*Transactions pages 308–12*).

Preventive Lightning Protection. Experience with protection against lightning on steel-tower transmission lines operating at from 66 to 220 kv has been analyzed and certain apparent trends reported as a basis for further study (*Transactions pages 249–54*).

Detecting Initial Insulation Failure. A study has been made of the stress at which initial discharge occurs in laboratory specimens of gas-free cable insulation and of the subsequent growth and other changes in the volume of the discharge (*Transactions pages 267–72*).

Electrolytic Scale Removal. Development and operation of electrolytic equipment for use in a continuous pickling line to assist the removal of oxide scale from strip steel are described in this issue (*Transactions pages 294–6*).

Summer-Convention Program. Complete program of the 1941 AIEE summer convention, to be held at Toronto, Canada, June 16–20, appears in this issue (*pages 282–3*); further details on the convention are also presented (*page 281*).

Storage Batteries in Transportation. A review of storage-battery applications in railroad, motor-bus, and aircraft transportation includes discussion of the changes made in battery construction for these services (*Transactions pages 303–07*).

Surges on a 12-Kv System. A theory for the explanation of system overvoltages has been developed on the basis of data observed and recorded for 20 years on the 12-kv system of a large midwestern city (*Transactions pages 260–5*).

Coming Soon. Among special articles and technical papers currently in preparation for early publication are: text of the presidential address by AIEE President R. W. Sorensen (F'19) at the summer convention in Toronto, and of an address at the summer convention on co-operative effort to insure the survival of the free-enterprise system by Howard Coonley; an article on high-voltage fluorescent tubing by J. A. McDermott (A'35); an article on fires of electrical origin in manufacturing plants by G. S. Lawler (M'13); a paper discussing the factors influencing the mechanical strength of cellulose insulation by F. M. Clark (A'24); a paper on atmospheric variations and apparatus flashover by P. H. McAuley (A'36); a paper describing the electrogear, a new electromechanical vehicle drive, by Ernst Weber (F'34); a paper on performance and power supply of large electric-arc furnaces by B. M. Jones (M'24) and C. M. Stearns; a paper dealing with rotor-bar currents in squirrel-cage induction motors by J. S. Gault (M'30); a paper outlining classification and co-ordination of short-time and intermittent ratings and applications by R. E. Hellmund (F'13); and a paper on volt-time areas of impulse sparkover by J. H. Hagenguth (A'28).

ELECTRICAL ENGINEERING: Copyright 1941 by the American Institute of Electrical Engineers; printed in the United States of America; indexed annually by the AIEE, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London). Address changes must be received at AIEE headquarters, 33 West 39th Street, New York, N. Y., by the 15th of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge.

Today . . . WESTON INTRODUCES A NOTEWORTHY ADVANCE IN THE ART . . . PHOTO-CELLS WITH CONTROLLED CHARACTERISTICS TO MEET SPECIFIC NEEDS!

Looking back to 1931...we see dimly lighted factories, and children straining precious eyes in poorly lighted schools and homes . . . our busy streets too often left unlighted during storms, or during the dangerous period at dusk . . . photographers still guessing at exposure, and color matching still *mis*trusted to the human eye.

But in that year, WESTON gave to industry the Photronic Cell . . . the first *commercially practical* dry-disc photo-cell. *Practical*, because it was permanent in calibration . . . required no outside power source . . . generated sufficient current even at low light levels to operate measuring instruments and relays . . . and possessed a spectral response which included that of the human eye. *All* the characteristics requisite for a direct-reading illumination meter . . . a foolproof exposure meter . . . an automatic light control system . . . a photelometer for directly indicating blood characteristics.

All these, and many more noteworthy developments closely followed the introduction of the Photronic Cell. Thus today we enjoy better seeing and better sight, increased safety, better health . . . and industry controls many processes better and at lower cost . . . thanks to the practical and permanent characteristics of this unfailing electric eye.

And Now—a New Service in Photo-Cells

As the pioneers and leading producers, WESTON introduces a new service in dry-disc photo-cells . . . the result of a decade of continuous cell production, and research in photo-cell design. It includes cells of various shapes and sizes, with fatigue practically eliminated, and with output, spectral response and other characteristics *controlled* to fit the need. With this new service, the American-made Photronic Cell ushers in a new decade of progress in which even greater utilization, and greater benefits can be expected from the dry-disc photo-cell. Weston Electrical Instrument Corporation, 664 Frelinghuysen Avenue, Newark, New Jersey.

**PHOTRONIC—A registered trademark designating the photoelectric cells and photoelectric devices manufactured exclusively by* WESTON.

Laboratory Standards . . . Precision DC and AC Portables . . . Instrument Transformers . . . Sensitive Relays . . . DC, AC, and Thermo Switchboard and Panel Instruments.

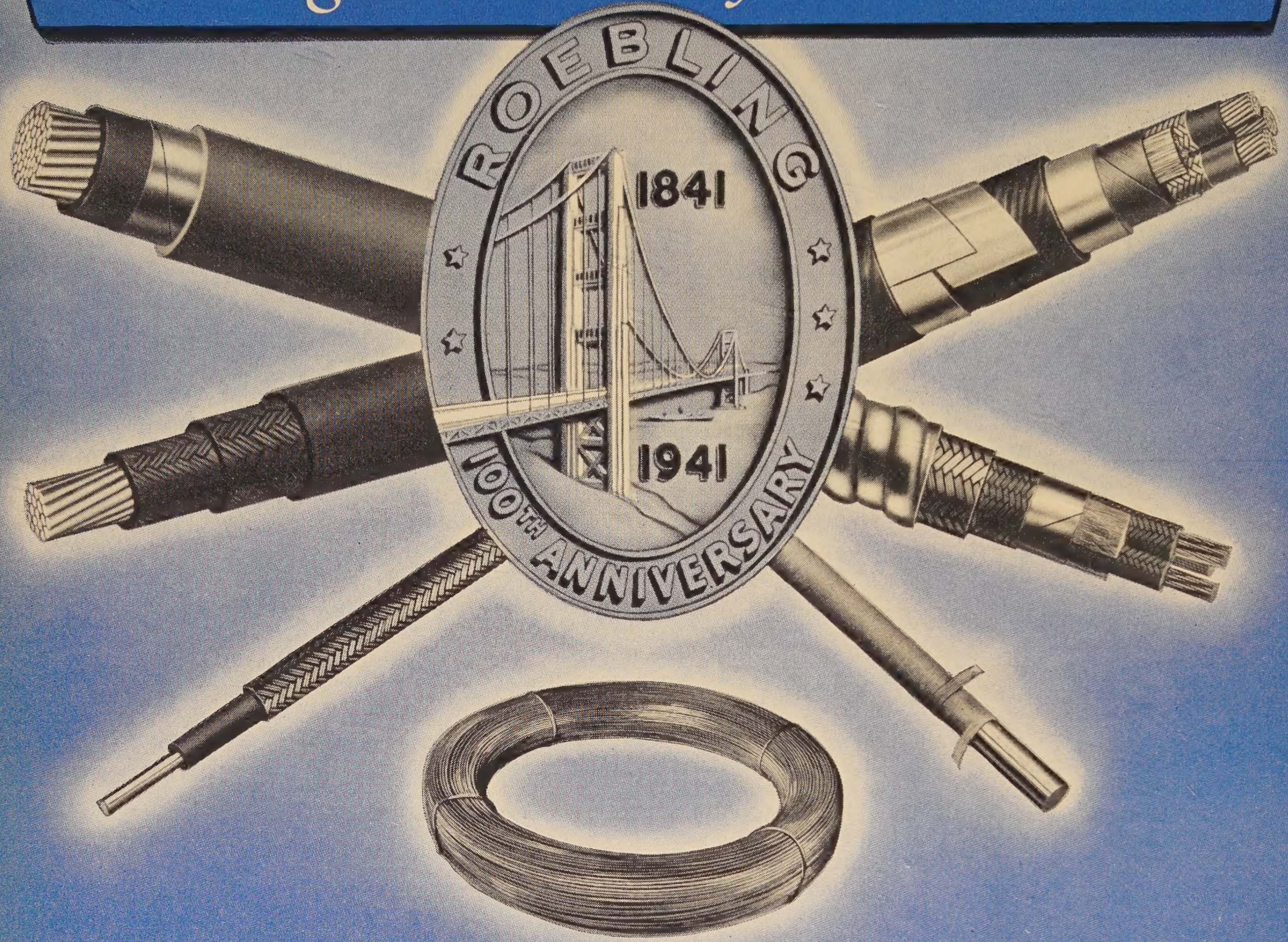
WESTON

Specialized Test Equipment . . . Light Measurement and Control Devices . . . Exposure Meters . . . Aircraft Instruments . . . Electric Tachometers . . . Dial Thermometers.

FOR OVER 53 YEARS LEADERS IN ELECTRICAL MEASURING INSTRUMENTS

ROEBLING

"Bridges a Century with Wire"



ROEBLING ELECTRICAL WIRES AND CABLES

100 years ago John A. Roebling founded the company which still bears his name. » » Today, after a century of service, the name Roebling is still synonymous with leadership in wire manufacture, improvement and application. » » In celebrating its 100th Anniversary, Roebling looks forward to the opportunity of serving industry in even greater measure than ever before.

JOHN A. ROEBLING'S SONS COMPANY

TRENTON, NEW JERSEY

Priorities in Men

HARVEY N. DAVIS

It is widely recognized that a "system of priorities" is necessary to assure proper control and ready availability of the enormous variety of raw materials and complicated military equipment essential to adequate national defense in these dangerous times. However, the parallel and equally vital need for assuring adequate supply and most effective use of the nation's limited supply of specially trained technical manpower seems to be not so widely recognized. Hence, Doctor Davis' strong and thoughtful plea for a system of "priorities in men."

IT MAY BE that an apology is due for my discussing again a topic on which I have had a good deal to say, both privately and publicly, for some months past. My excuse is twofold. First, it seems to me to be an extremely important problem that I am trying to deal with. And second, the crux of it seems to me to be the attitude which the rank and file of the American people is going to take with respect to it.

What an enlightened public opinion understands and demands can and will be done. And on the other hand, what public opinion does not understand, and is likely to misinterpret, cannot be done, no matter how wise those in authority may be, or how clearly they realize the need for doing it. Each one of us has, therefore, an opportunity, and a responsibility, to make clear to the public in every community in which our influence is felt what the nature of this problem is, and what we think should be done about it. Only by constant repetition, on every suitable occasion, can this be done. If, therefore, I repeat some of the things I have said on other occasions, it is because I hope to persuade you to say them elsewhere, over and over again, so as to help both to crystallize and to sustain that public understanding that alone can make wise action possible.

The United States has at last plunged into the most considerable defense program of its history. We have decided to build a two-, if not a three-, ocean navy. We have decided to recruit and train an army sufficient to ensure the future safety and independence not only of ourselves but of any of our neighbors in the Western Hemisphere that may need our help. We have decided to mechanize that army. We have also decided that our own future welfare demands that Hitlerism shall cease to be a potent factor in world affairs. We have set out to prove that the world is no longer the kind of place in which his medieval lust for power can successfully gorge itself on the sufferings of others. We have decided to try to make it clear that this is no longer a world in which such actions can even temporarily pay. In most parts of the world it no longer pays to try to be a private highwayman. I like to think that it no longer pays to try to be an international highwayman, and that it is for the purpose of making this fact clear to all that we are rearming.

Finally, we have decided that the heroic fight that Britain and her allies are putting up is our kind of fight, and that we are going to back that fight with all the munitions of war and all the ships and all the food we can produce for them. For once in my life I find myself in complete accord with the foreign policy of my country. To my mind the only question is: How can we best accomplish what we have set out to do?

Already we are beginning to fear, and in some cases actually to encounter, shortages of certain essential raw materials such as aluminum and nickel. To some extent these current shortages are not real, but are merely reflections of the excitement of these stirring times, of over anxiousness on the part of munitions makers to protect themselves against possible future difficulties. But even so, everyone agrees that the way to meet the situation is to establish a system of priorities which will ensure that the available supplies of these raw materials will go where they will do the most good to the nation.

By the same token we are already facing acute shortages of certain kinds of trained man power, and here there is no question but that the shortages are real and not merely psychological. I suggest that in every such case it is our national duty to conserve to the utmost whatever pool of trained men we already have, and this not merely on a local, but on a nation-wide basis. This means establishing a system of priorities in man power as we have in raw materials.

As a first step toward establishing such a system of priorities in men, we must realize that, at least at present, production is far more important to national defense than is combat training. Modern armies are helpless not only without guns and ammunition, but also without airplanes and tanks and trucks and all the other mechanical equipment of modern warfare. One completely mechanized division nowadays is better than two or three divisions of the old-fashioned sort. And, on the other hand, it takes two or three times as many workers on the industrial front to equip and maintain a mechanized division on the battle front, as it used to take for an old-fashioned division of foot soldiers. A far larger proportion of the total fighting strength of a nation today must be allocated to its factories as compared with its battlefields than was the case in World War I.

Address presented at the AIEE North Eastern District meeting, Rochester, N. Y., April 30–May 2, 1941.

Doctor Harvey N. Davis is president of Stevens Institute of Technology, Hoboken, N. J.

This brings me to the crux of the whole matter. What should be your attitude and my attitude and the attitude of the public generally toward the relative priorities of industry and of the draft with respect to trained men? My own belief is that, at least for the present, no trained man who is likely to be useful in production, no matter how young or inexperienced he may be, should be drafted from industry or on his way from college into industry. Whether the situation will be entirely different six months or a year hence, no one can now foresee. As things are now, however, I believe that the needs of the defense industries should be given almost absolute priority over combat training.

In saying this, I am not in the least interested in whether any particular young man wants, in the bottom of his heart, to hide under the bed when war is mentioned, or whether, as is much more likely, he enthusiastically wants to don a uniform and get into the thick of combat training. Unfortunately, there is nothing glamorous about sticking to one's job in the factory when one's friends are marching off behind a band and every man in khaki is a hero. None of these sentiments interest me in the least with respect to the young men I am talking about. What I want is to have every one of them put where he will do our country the most good. At present, in the case of any man who has something vital to contribute to production, I believe that his rightful place is on the industrial front rather than in the Army. Whenever a young man has a kind of training that makes him better fitted than average to take part in defense production, or whenever he is undergoing training of that sort, it is, I think, a matter of duty for his present or prospective employer to ask for his deferment. If the firm for which he is working is not engaged in defense production to such an extent as to seem to justify them in asking for deferments for their production men, then each such man likely to be drafted should be turned loose and helped to place himself where his work will contribute to defense production, and he should not be replaced.

I say this because production men of all levels are already getting very scarce in this country. That this is true of the rank and file of factory operatives is indicated by the statement recently made to me that in one defense industry, six months ago, 50 to 60 per cent of those applying for employment were deemed suitable for training for the kind of work in question, whereas now only 25 to 30 per cent of the run-of-mine applicants can be used. For some time men with skill and experience in the various branches of the machinist's trades have been as scarce as hen's teeth, and expert tool and die makers are simply not to be had. Good foremen are scarce and not easily trained. To find or make supervisors for the next higher levels is a very serious problem in many rapidly expanding defense industries. And so on right up the line to the top. As to the top itself, I have been told that the most serious obstacle that has prevented an even more rapid expansion of aircraft production has been the limitation that nature imposes on the physical and nervous strength and stamina of the top executives who have to do the planning of every extension of plant or augmentation of working force. Under these circumstances I believe that no man skilled in, or in a fair way to soon become skilled in, any phase of production should be permitted to divert his attention to the manual of arms at this crucial moment in our history. As Commissioner Studebaker of the United States Office of Education recently said: "The future of democracy depends on the efficiency of the 'arsenal of democracy'. That efficiency depends on the skill of workers and management."

In applying this general principle to particular cases, the only question seems to be the probable value of each individual to the production program. In the case of engineers, the relationship is unusually direct and obvious. Industrial production has been, for at least 40 years, the especial concern of the engineer. There are far more engineers today actively engaged in planning, directing, and controlling industrial production than there are in the traditional engineer's work of designing the product to be produced, or doing the development work on which that design is based. The typical engineer of today is in general very far from the pure technician that the public commonly thinks he is. He is on the firing line of the industrial front. And that is where the nation most needs to have him.

But there are many others who are playing or will soon have to play important parts in the production program. Among them are men trained in all phases of management. To increase the output of a factory by improving the technique of its management is a far quicker and more effective way of speeding up production than is building a new plant. I venture to assert that if the average level of management in American plants could be brought up to the level of the management of the top tenth, or even the top fourth, of present-day management, to say nothing of the almost certain advances in the art that widespread concentrated attention on this field of work would produce, the resulting effect on production would be very great. And let us not forget that economists, sociologists, and particularly psychologists would have an important part to play in such an industrial revolution, as well as a host of teachers, counselors, and even propagandists, working on and through the administrative personnel of industry.

Whether the establishment of an effective system of priorities in men should be undertaken by means of officially prescribed "reserved occupations", as in England, or as we are trying to do it here now is a serious question.

Undoubtedly local draft boards have ample power under the present selective service law really to select, with the needs of the industrial as well as the combat front always in mind. Recently Brigadier General Lewis B. Hershey, director of selective service, reminded state directors of a provision in the act that it must be administered so that it will not interrupt, delay, or impede the national defense program. "There is," he said, "a dual responsibility imposed upon local boards. They must not only select those who are needed by the armed forces, but must also defer those who are necessary in the production of defense materials. They must take fully into consideration the entire defense picture in making that selection or deferment."

That they shall do just this, is, I believe, the earnest desire and hope of those who have the best interests of the Army itself closest to their professional hearts. Andre Maurois has repeatedly cited as the first of the three or four mistakes that he regards as leading to the fall of France the diversion of too many men from defense production to combat service. One high-ranking Army officer in Washington was quoted to me recently as having told a tale of his own experiences during World War I. He had been put in charge of whipping into shape a regiment of draftees, and, after putting his best into them for some three months, had them just about ready to send abroad. Suddenly some one in Washington discovered that the draft had hamstrung various munitions industries. Thereupon an order went out that all draftees with such and such skills and such and such experience were to be immediately undrafted and sent back to their jobs. As it happened, the order hit this particular regiment particularly hard, for when it had been complied with there was scarcely a corporal's guard left. "And there was I," the officer said, "with three months of enthusiastic work utterly wasted; and there were my men, also with three months wasted, back on the jobs they should have been left at in the first place. I hope the draft boards don't load us up with a lot of men of that same sort again."

Another high-ranking Army man in Washington, whose job is to further the procurement work of the Army, is quoted to me as having recently said, "The trouble is that a lot of these industrial fellows think it is noble and patriotic not to ask for the deferment of any man who hasn't been with them at least six months. Take such and such a company in your area. We've been working on them for three months now, and at last we've pounded some sense into them. They're beginning to ask for the deferments they ought to have been asking for all along."

That's the way the draft situation looks to some of the career men of the Army itself. If any of you are employers of skilled men that ought to be playing a part on the production side of national defense, I hope you will take these two tales to heart, and ask for the deferments that it is your patriotic duty to ask for. And remember that you must state your case clearly and fully and put up a real fight for the deferment of each individual man. Otherwise you won't give a local draft board a leg to stand on in doing what it knows to be wise. It cannot take the initiative; you must.

On the whole our noncentralized method of tackling the priorities in men is working pretty well. I myself have a good deal of faith in the soundness and power of an enlightened public opinion, and in the eagerness and ability of all our constituted authorities, including, in particular, our local draft boards, to act with all the wisdom that their constituencies will permit.

But if we are going to make such a system really work in the still darker days that probably lie ahead, some way must be found to make the decisions of our more than 4,000 local boards more nearly consistent with each other in various parts of the country, in urban and suburban areas, in single industrial areas, and even in different parts of one small city. Merely reporting in summarized statistical form the actions of each board for the benefit of all neighboring boards might help greatly to stem the growing tide of discontent with such inconsistencies as that a second-year student in a certain medical school was deferred by one local board while a third-year student of equal ability in the same school was not deferred by another local board. Such inconsistencies are likely to undermine the morale not only of the general public, but of the draft army itself. Furthermore the young men just about to graduate from our schools of engineering and of business administration want to be able to plan at least a little ahead with at least some assurance as to what this or that local board is going to do. Under our present system these inconsistencies and uncertainties can be minimized only by a vast deal of education of all our draft boards, and even more importantly, of all our citizens as to the serious problems that are involved in this whole matter of priorities in men. Unless this education, which you must help carry on, is effective, we may be forced to adopt by law something much nearer to the British system.

President James Bryant Conant of Harvard University has just returned from a two-months trip to England, and his first published article on the English situation is to be found in a recent issue of the *Harvard Alumni Bulletin.** In that article he discusses at some length this matter of priorities in men as it is being worked out in a country far more in need of combat man power than we yet are. His report deserves very thoughtful attention, for it may point the way to what we shall soon have to do here, if we are to succeed in helping to preserve democracy in the world by making it work effectively. He says, in part:

"It is now clearly evident that the British government was far-sighted in developing the idea of 'reserved occupations' before the war. I am not in a position to report on the way the regulations under the act have affected industrial man power, but it is manifest that without these schemes the scientific brain power of the country could not have been properly adjusted to the needs of a modern war.

"The Schedule of Reserved Occupations, first proclaimed in January 1939, by authority of Parliament, listed a thousand or more categories of employment which were then regarded as essential to the defense of the country. Only a dozen or so involved university-trained men, but those dozen were, as events have proved, highly important. They included, for example, architects, university professors and lecturers, school teachers, various types of engineers, scientists, and, of course, medical men, including dentists. Each category was assigned an age limit; men above this age were 'reserved', irrespective of the particular industry in which they were engaged—that is, these men were only permitted to volunteer for a restricted classification of war services. The more vital the occupation was to the national defense, the lower the age at which reservation commenced. For example, doctors were reserved at all ages, physicists at 25, chemists at 21, university teachers at 25, secondary school teachers at 25.

"It is important to note that originally the only consideration involved in drawing up this schedule was the anticipated importance of each category of work to a total war effort. There was no idea that certain types of men should be reserved because they were too valuable for peacetime activities to run the risks of war. To have tried to introduce such an idea into the scheme would have been disastrous both to morale and to the practical applications of the basic concept. At the same time it must be remembered that, since an occupation as such was reserved (above a certain age), a man's

* The British Universities and the War, James Bryant Conant. *Harvard Alumni Bulletin*, April 26, 1941, pages 813–16.

particular job within an occupation was not then taken into account. It must have been recognized at the outset that by the application of such a blanket procedure many occupations would initially be 'overreserved'. This was certainly the case with some types of university-trained men and undoubtedly the case with many skilled and semiskilled trades. But the possibility always existed of (1) subsequently 'de-reserving' an occupation, or (2) raising the age of exemption within a given occupation, or (3) introducing a new principle, namely that the particular job on which a man was engaged must be essential to the national work. Now, after 18 months of war, all these changes have been made.

"The schedule is about to undergo still another revision. In many occupations the age limit is being raised, since experience now shows that, on balance, the needs of the fighting services are more important for the national effort than the particular occupations in question. . . . On the other hand, the age limit on physicists who have proved of the utmost importance to 'war work', has been lowered from 25 to 21. Certain industrial occupations have been removed from the list, and the principle has been now adopted that every man reserved is not merely available for essential work, but is in fact engaged upon it. It should be emphasized, however, that if this last principle had been adopted at the outset, no reservoir of men for new essential work—either scientific or industrial, the result of wartime experience—could have been created.

"The creation of certain reserved occupations involving university men had the effect of bringing into existence a pool of highly trained scientists from which the government could draw as the need arose. To assist the government in this process the Central Register was created. This extremely important agency is now a department of the Ministry of Labor. It has done splendid work and is a vital part of the war effort. At first, registration was voluntary, but last summer the shortage in certain professions was so apparent that the government required physicists, chemists, and engineers to register."

Atom Smashing and Its Applications to Medicine

ROBLEY D. EVANS

A review of the elementary principles of atomic structure and atomic transmutation introduces some typical applications of the method of "tracer" or "spy" atoms to medical problems

INVESTIGATIONS of the structure of atoms have shown that each atom possesses at its center a small, dense, positively charged core, or nucleus. Outside the nucleus the atom consists only of a small swarm of electrons, which are negatively charged and whose number is just sufficient to provide enough negative charge in the atom to balance the positive charge on the nucleus, so that the complete atom is electrically neutral. It is possible to modify the structure of atomic nuclei and thus to produce new atoms having unusual properties. In many cases these artificial atoms are radioactive and can be usefully applied in engineering, physics, chemistry, geology, and medicine.

ATOMS AND NUCLEI

In modern scientific activities only the engineer deals with objects whose dimensions can be readily appreciated by the human mind. Thus the height of a man, the length of a bridge, the weight of a turbine, or the speed of a motor car are all magnitudes that we can appreciate readily through our fundamental senses. This domain lies midway between those with which the astronomer and the nuclear physicist must deal. On the one hand, the astronomer is concerned with distances and masses and times so vast that we cannot appreciate their size, as compared with the experiences of everyday life. At the opposite end of the scale, in the domain of the atomic and nuclear physicists, the dimensions are so minute as to challenge comprehension.

Being small, atoms are also numerous. If we were capable of marking every atom in a glass of water, so that we could recognize that atom if we found it again at a later time, and were then to pour that glass of water into the ocean and allow it to become thoroughly mixed with all the water in all the lakes, rivers, seas, and oceans of the entire world, we would find that every glass of water, regardless of what part of the world samples were taken from, would contain over 5,000 of our original marked atoms.

The glass of water contains about 20 million million million million atoms. Let us imagine that we can enlarge the scale of this glass of water, or contract our own physical dimensions, until we are able to see and examine the individual atoms and their internal structure. If we were to enlarge the scale to make the glass so big that it could contain the entire earth, we would be able to see the individual atoms, each of which would be about 1 inch across. Further examination of these 1-inch atoms would reveal very little, for we would find each of them to consist of a nucleus and a small number of electrons, the dimensions of each of these particles being only a few millionths of an inch. Thus the atom is mainly empty

An address presented at the AIEE winter convention, Philadelphia, Pa., January 29, 1941.

Doctor Robley D. Evans is associate professor of physics at Massachusetts Institute of Technology, Cambridge.

space, but it retains its shape and its volumetric displacement by virtue of its very strong internal electric fields.

To be able to see anything in our atom we must again expand the scale. We must make our glass of water so big that the sun could be placed at its center as a tiny pinpoint, and that Mercury, Venus, and the earth could easily traverse their regular orbits about the sun with plenty of room to spare inside the glass. Under those circumstances we could see the individual particles which comprised the atom. If, for example, we chose to examine an atom of oxygen in the water, we would find it to be a roughly spherical object having a diameter of about 10 miles. Occupying this 10-mile spherical space we would find 8 electrons and at the center 1 nucleus, each of these 9 particles being only about the size of a child's toy balloon. Only the very outermost electrons, at the edge of this 10-mile sphere, are involved in ordinary chemical and biochemical reactions. The inner electrons, and especially the atomic nucleus, remain relatively unaware of the chemical or biochemical activity of the outer electrons of the atom.

We may now go to the center of this 10-mile oxygen atom and examine the nucleus. Close inspection would show the nucleus to be a closely packed group of individual particles, like a bunch of large grapes. The oxygen nucleus, if we had maintained its density constant during our expansion of its dimensions, would weigh 500,000 million tons. It would consist of 16 closely packed particles, of two types. There would be 8 particles, called "protons" each having unit positive charge. There would be 8 more particles of substantially the same size and mass as the protons, but having no charge. These neutral particles are called "neutrons." These neutrons and protons are very much alike, and when it is conducive to the formation of a more compact and stable nucleus, neutrons are actually capable of changing themselves into protons, and vice versa. Thus the neutron and proton may be regarded as alternate aspects of one fundamental but unnamed nuclear particle. There appear to be no other particles aside from neutrons and protons in the atomic nucleus; particularly there are definitely no electrons in the nucleus. In the oxygen atom, whose nucleus contains 8 protons and hence shows 8 units of positive charge, there are 8 electrons disposed within the 10-mile sphere that is our atom.

If we examine a large number of oxygen nuclei we shall find a few rare ones which contain 17 particles in the nucleus, and others which contain 18 particles. Like the abundant normal type, each of these nuclei contains 8 protons, hence has a positive charge of 8 units, and hence requires 8 electrons for the formation of a neutral atom. Since the chemical properties are dictated by the number and configuration of the electrons, chemically all these atoms will behave identically. They are therefore called "isotopes"; that is, they have the "same place" in the Mendeléeff periodic table of the chemical elements. These nuclei differ from one another only in the number of neutrons which they contain. Since nearly all of the mass is concentrated in the atomic nucleus, because of the relative lightness of the electrons, these three types of oxygen atoms will have different atomic weights. The "atomic number" of an atom is simply the number of protons in its nucleus, and the "atomic weight" of an atom is given by the total number of neutrons and protons in the nucleus. Thus the atomic weight of ordinary oxygen is 16 while the atomic weights of its two heavier isotopes are 17 and 18.

The simplest atom is that of ordinary hydrogen, whose nucleus consists of a single proton, and which has but 1 atomic electron. The next most complicated atom in nature is that of heavy hydrogen, whose nucleus contains 1 proton and 1 neutron. Again there is but 1 atomic electron, hence the chemical properties are those of hydrogen, although the chemical atomic weight is about twice that of ordinary hydrogen. The next most complicated common atom is that of helium, whose nucleus contains 2 protons and 2 neutrons. The neutral atom of helium therefore contains 2 atomic electrons, and helium has an atomic weight of 4. This helium nucleus of 4 particles, 2 neutrons and 2 protons, is of especially great interest in nuclear physics, as it is a highly stable subunit in heavier nuclei.

All the 278 known stable isotopes of the 92 common chemical elements differ from one another only in the number of neutrons and protons in their nuclei. If two nuclei have the same number of protons, they are called isotopes, and they belong to the same chemical element. If they have the same total number of particles, then they have the same atomic weight and are called "isobars", and in general they will belong to different chemical elements, because the number of protons will be different.

In nuclei the neutrons play the role of a binding cement which holds the entire nucleus together in spite of the very strong electrostatic repulsive forces which the positive protons exert upon one another. Thus in the heavier nuclei we will find a slightly larger proportion of neutrons in the nucleus in order to overcome the rapidly mounting repulsive forces between the larger number of protons. The most complicated nucleus known in nature is the heavy and more common isotope of uranium. This nucleus contains 92 protons; hence uranium has an atomic number of 92 and the neutral uranium atom contains 92 electrons. This nucleus also contains 146 neutrons, making a total of 238 particles in the nucleus; hence the atomic weight is 238. Uranium, like several other heavy elements such as thorium and radium, is not a completely stable nuclear configuration, possibly because of its excessive weight and complexity. It can become more nearly stable by splitting off from itself a helium nucleus, or alpha particle, and expelling this nuclear fragment from the nucleus. This is the origin of the alpha-ray radioactivity of heavy elements, and we shall find that the swiftly moving alpha ray or helium nucleus has found very great usefulness as an atomic bullet.

Figure 1 is a plot which shows each of the known stable nuclei as a square. These nuclei appear to represent all the stable configurations that can be made by taking an arbitrary number of protons, corresponding to particular values of the atomic number, and adding neutrons in such numbers that stable nuclei result. A number of gaps appear in the vertical groups of isotopes in figure 1, from which we can infer that these positions represent unstable

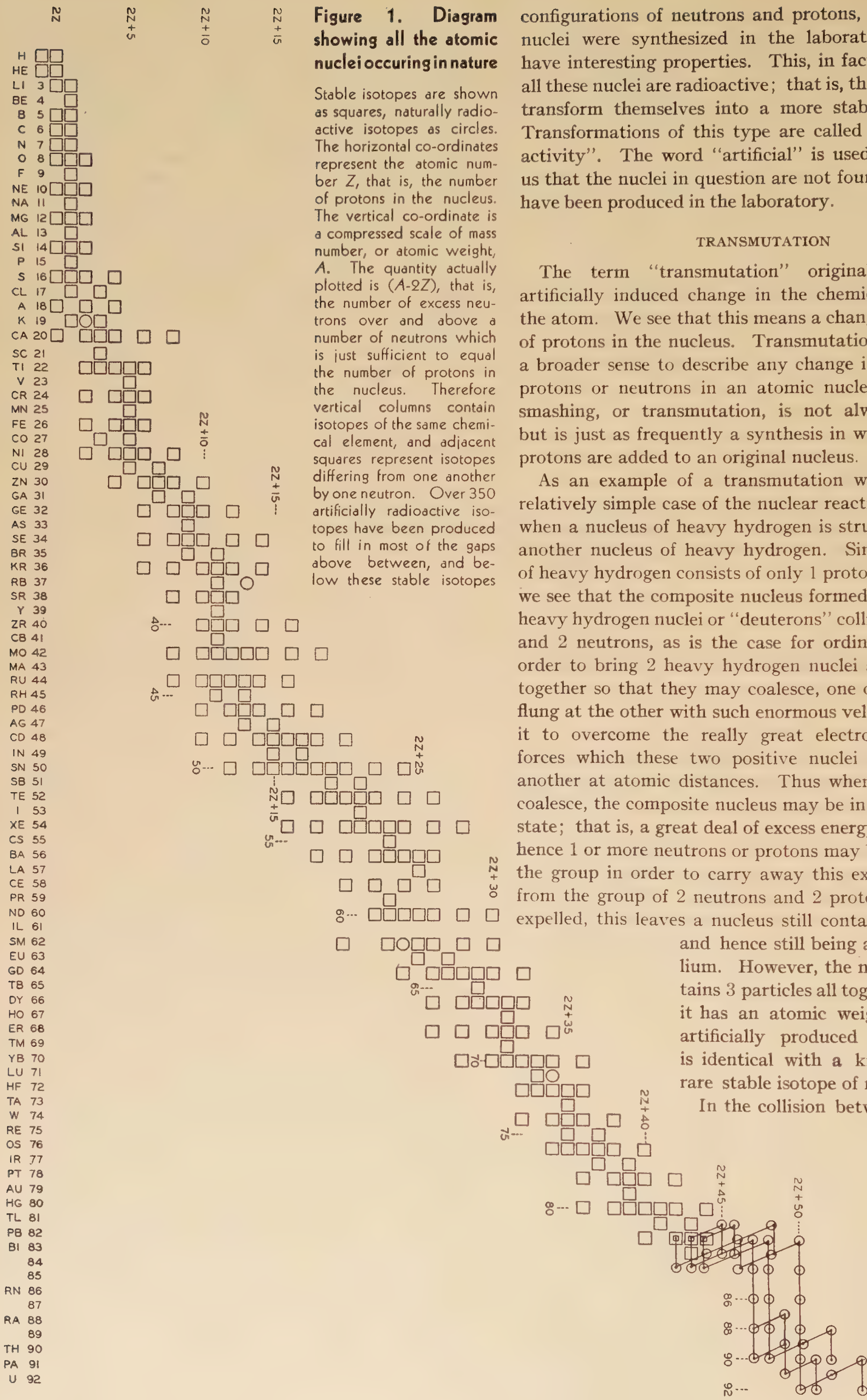


Figure 1. Diagram showing all the atomic nuclei occuring in nature

Stable isotopes are shown as squares, naturally radioactive isotopes as circles. The horizontal co-ordinates represent the atomic number Z, that is, the number of protons in the nucleus. The vertical co-ordinate is a compressed scale of mass number, or atomic weight, A. The quantity actually plotted is $(A-2Z)$, that is, the number of excess neutrons over and above a number of neutrons which is just sufficient to equal the number of protons in the nucleus. Therefore vertical columns contain isotopes of the same chemical element, and adjacent squares represent isotopes differing from one another by one neutron. Over 350 artificially radioactive isotopes have been produced to fill in most of the gaps above between, and below these stable isotopes

configurations of neutrons and protons, and that if such nuclei were synthesized in the laboratory, they might have interesting properties. This, in fact, is the case, for all these nuclei are radioactive; that is, they spontaneously transform themselves into a more stable configuration. Transformations of this type are called "artificial radioactivity". The word "artificial" is used only to remind us that the nuclei in question are not found in nature, but have been produced in the laboratory.

TRANSMUTATION

The term "transmutation" originally implied an artificially induced change in the chemical properties of the atom. We see that this means a change in the number of protons in the nucleus. Transmutation is now used in a broader sense to describe any change in the number of protons or neutrons in an atomic nucleus. Thus atom smashing, or transmutation, is not always a smashing but is just as frequently a synthesis in which neutrons or protons are added to an original nucleus.

As an example of a transmutation we may take the relatively simple case of the nuclear reaction which occurs when a nucleus of heavy hydrogen is struck forcefully by another nucleus of heavy hydrogen. Since each nucleus of heavy hydrogen consists of only 1 proton and 1 neutron, we see that the composite nucleus formed when 2 of these heavy hydrogen nuclei or "deuterons" collide has 2 protons and 2 neutrons, as is the case for ordinary helium. In order to bring 2 heavy hydrogen nuclei sufficiently close together so that they may coalesce, one of them must be flung at the other with such enormous velocity as to allow it to overcome the really great electrostatic repulsive forces which these two positive nuclei exert upon one another at atomic distances. Thus when the two nuclei coalesce, the composite nucleus may be in a highly excited state; that is, a great deal of excess energy is present, and hence 1 or more neutrons or protons may be expelled from the group in order to carry away this excess energy. If from the group of 2 neutrons and 2 protons a neutron is expelled, this leaves a nucleus still containing 2 protons, and hence still being an isotope of helium. However, the nucleus only contains 3 particles all together, and hence it has an atomic weight of 3. This artificially produced "light helium" is identical with a known but very rare stable isotope of natural helium.

In the collision between two nuclei

of heavy hydrogen a composite nucleus is formed, a neutron is expelled, and there remains a nucleus of light helium. Thus a transmutation has taken place: 2 atoms of hydrogen have been combined to form 1 atom of helium, and also a free neutron, which escapes from the apparatus. The atomic electrons play no role in these transmutations, but merely follow their atoms around as best they can. In the present case the 2 electrons originally associated with the 2 atoms of hydrogen are needed in the formation of the neutral atom of helium.

The process of atomic transmutation therefore consists of knocking nuclei together in such a way as to change the number of neutrons or protons or both. All the important basic discoveries in nuclear structure and atomic transmutation were obtained by using the alpha particles from radium, and from other heavy radioactive substances, as atomic bullets with which to bombard other nuclei.

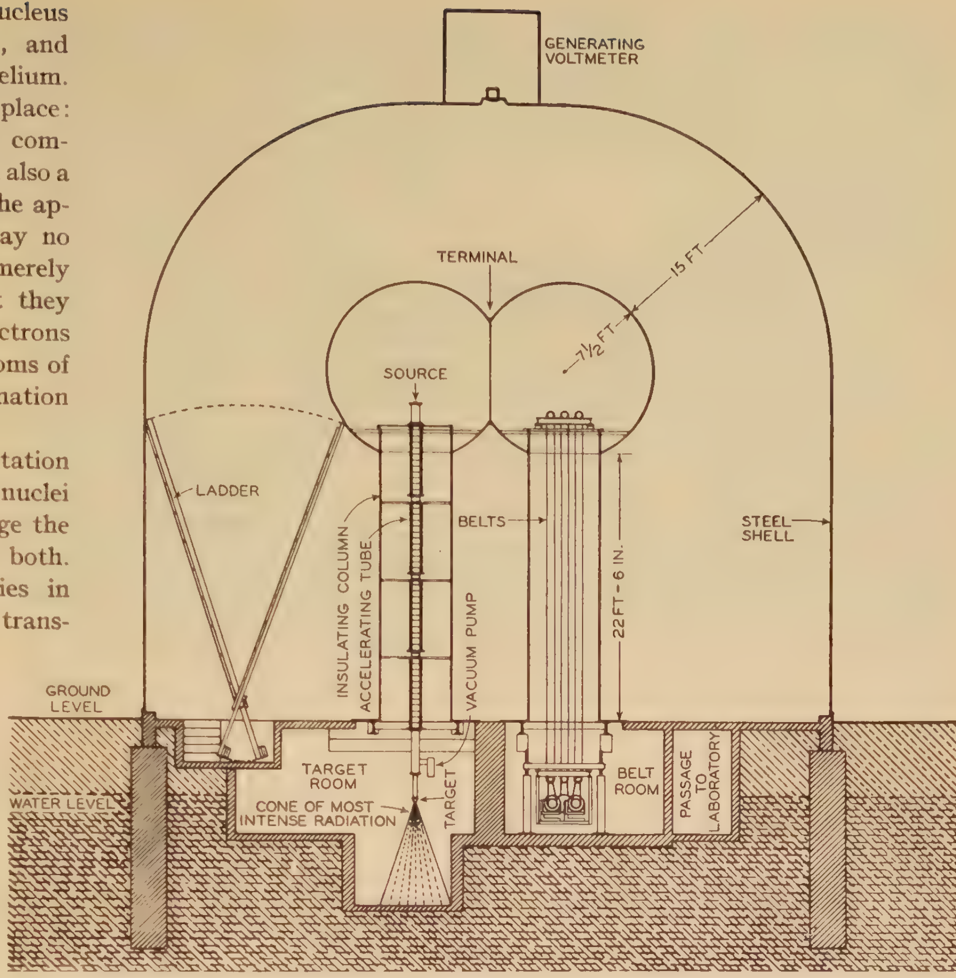


Figure 2. Cross-sectional diagram of the 2,500,000-volt Van de Graaff generator at the Massachusetts Institute of Technology

ATOM SMASHERS

The alpha rays from the natural radioactive substances have very great velocity, some of them moving faster than 2×10^9 centimeters per second, which is 1/15 of the velocity of light and thus would allow them, if unimpeded, to go around the earth in less than two seconds. The energy of any swiftly moving nuclear particle is usually expressed in millions of electron volts. The kinetic energy of the common alpha ray is about 5,000,000 electron volts, which is vastly greater than the kinetic energy obtainable by any known mechanical means. This can be seen by noting that the kinetic energy of each atom in a high-speed rifle bullet is less than 1/10 of an electron volt. Thus the alpha particle has some 50,000,000 times the kinetic energy of the atoms in a rifle bullet.

To smash atoms more abundantly and in a greater variety of ways than is possible with alpha rays alone, it is desirable to put simple atomic nuclei such as those of hydrogen (proton) and heavy hydrogen (deuteron) into high-speed motion. This can be accomplished by producing ionized hydrogen atoms—that is, hydrogen nuclei—in a hydrogen arc, and then accelerating the protons or deuterons thus produced through a discharge tube across which is a potential of several million volts. Electrical devices for artificially accelerating nuclear particles therefore have come to be known as "atom smashers." These atom-smashing machines are often of very great size, and their construction[1,2] and operation involves the advanced principles and practice of electrical engineering.

In the Van de Graaff generator[3] positive electric charge is sprayed, by means of corona points, onto a rapidly moving insulating belt, which carries and delivers this charge to an insulated electrode. This positively charged electrode is then made one of the terminals of a vacuum tube, and protons, deuterons, and other charged particles can be accelerated down this discharge tube and given exit velocities corresponding to several million volts of energy (figure 2). In the Van de Graaff generator the accelerated ions all have substantially the same energy, and this homogeneity, together with the great flexibility and accuracy of its voltage control, makes the electrostatic generator very suitable for detailed fundamental studies of the energetics of nuclear reactions. The maximum voltage obtained by the electrostatic generator is determined by the breakdown potential between the high-voltage terminal and its surroundings. By placing the apparatus in a compressed gas, terminal voltages of between 3,000,000 and 5,000,000 volts have been obtained.

It has been found that larger yields of smashed atoms are obtained as the energy of the bombarding protons, deuterons, or other nuclear particles is increased. To obtain artificially accelerated particles having energies above 10,000,000 electron volts, and hence having a very high atom-smashing efficiency, the cyclotron[4,5,6] is the

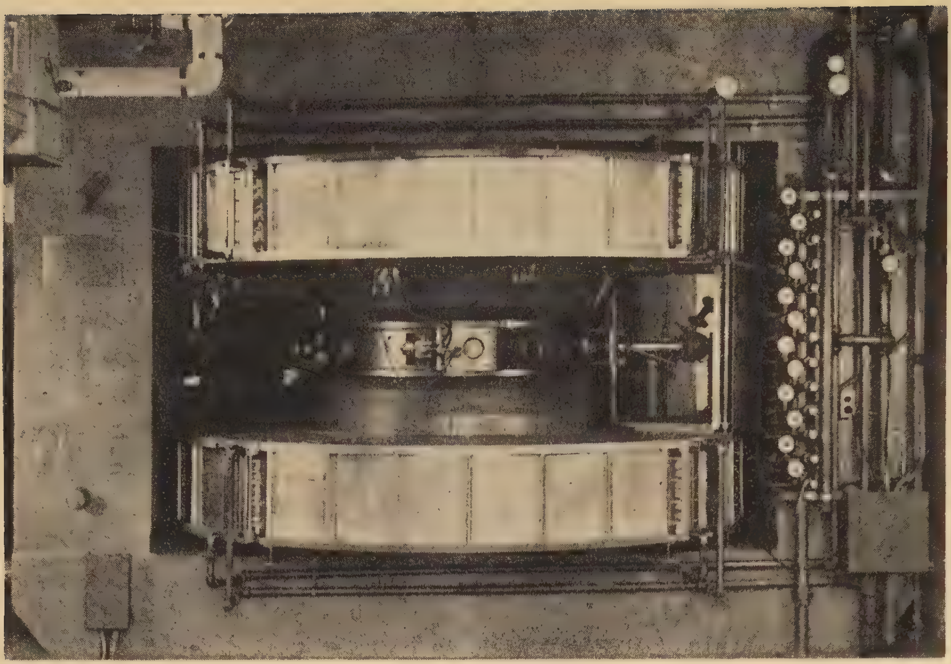


Figure 3. The 42-inch cyclotron at the Massachusetts Institute of Technology. The vacuum chamber can be seen between the poles of the 90-ton electromagnet

angular velocity of any one type of charged particle moving in a magnetic field is independent of the particle's linear velocity or energy, all such semicircles can be traversed by the ion in equal time intervals. After describing a semicircular path inside one of the electrodes, they emerge at its edge, and again enter the gap between the Ds, at a time which is one-half of a radio-frequency cycle later. They are again accelerated across the gap between the electrodes, and enter the opposite D, where they describe a slightly larger semicircular path. Coming once more to the gap between the Ds, the now reversed potential again accelerates them. Thus the ions continue, in resonance with the radio frequency and an appropriate fixed value of the magnetic field, to describe one semicircle during each half-cycle of the radio frequency. After 100 or more cycles their high velocity brings them to semicircular paths whose radius equals the radius of the D-shaped electrodes, and they finally are drawn out of the apparatus by an auxiliary negatively charged deflector plate and allowed to pass out of the vacuum chamber through a thin foil window. Just outside this window, or inside it if preferred, is placed a target containing the chemical element in which transmutations are to be produced.

best machine which has been developed up to the present time (figure 3). There are now some 15 or 20 cyclotrons of various sizes in operation in the United States, and about twice that number in the entire world. Each of these cyclotrons produces a much larger yield of atomic-transmutation products than could be obtained by the combined use of the alpha rays from all the refined radium in the entire world.

In the cyclotron, protons, deuterons, or other atomic ions are produced at the center of an evacuated chamber, and then are given a succession of 100 or more individual accelerations through a voltage of about 100,000 volts. Each ion therefore emerges from the apparatus with the same kinetic energy which it would have obtained in a single acceleration through a potential difference of some 10,000,000 volts.

Basically, a cyclotron consists of three main components, together with controls. The largest component is an electromagnet for producing a steady magnetic field of the order of 16,000 gausses between two large parallel circular pole pieces. Between these poles is placed a flat circular vacuum chamber containing two hollow D-shaped electrodes. In this evacuated chamber the ions move in a series of semicircular paths between voltage accelerations; hence the name cyclotron, which means "circle tube." The two hollow D-shaped electrodes in the vacuum chamber are connected to the terminals of a radio-frequency oscillator operating in the range between 10 and 15 megacycles, and usually having a power input of the order of 50 kw.

Positive ions produced near the center of the gap between the D electrodes are accelerated toward and into the hollow, negative electrode. There, in the absence of an electrostatic field, they describe a semicircular path due to the side thrust from the magnetic field. Because the

ARTIFICIAL RADIOACTIVITY

Bombardments of atomic nuclei with protons, deuterons, alpha particles, gamma rays, neutrons, and electrons have produced several hundred successful transmutations, including transmutations of every known stable chemical element. In many of these transmutations the final nucleus produced is identical with one which is already known in nature. However, in more than 350 cases the final nucleus produced is not known in nature, and is therefore artificially radioactive. Artificially radioactive isotopes of every known stable chemical element have been produced and studied.[7]

There are actually five distinct kinds of radioactivity. We have already discussed the case of alpha-ray radioactivity, which is common among the heavy naturally radioactive substances such as uranium, thorium, and radium. Among the artificially radioactive substances, beta-ray radioactivity is most common. This consists of the emission either of negative electrons or of positrons. The fourth type of radioactivity, or spontaneous transmutation, is electron capture, in which the atomic nucleus combines with and destroys one of its atomic electrons. The fifth type is the so-called "isomeric transition," which involves only a shift in the configuration of the

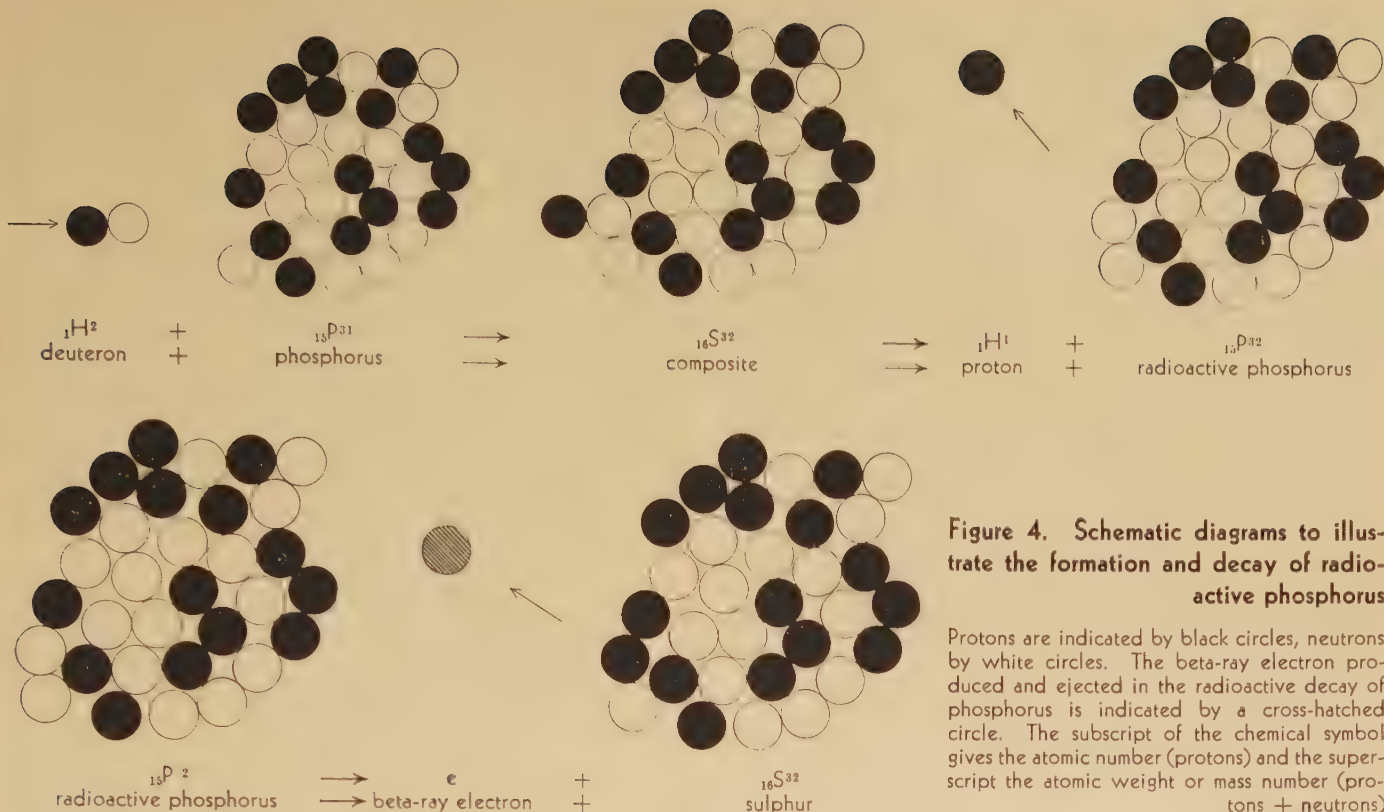


Figure 4. Schematic diagrams to illustrate the formation and decay of radioactive phosphorus

Protons are indicated by black circles, neutrons by white circles. The beta-ray electron produced and ejected in the radioactive decay of phosphorus is indicated by a cross-hatched circle. The subscript of the chemical symbol gives the atomic number (protons) and the superscript the atomic weight or mass number (protons + neutrons)

neutrons and protons in the nucleus without any change in the number of either. In the largest number of cases, the artificial radioactivity is of the negative-electron beta-ray-emitting type. We can gain a better understanding of artificial radioactivity by examining the reactions which take place in a particular case; for example, that of the formation and disintegration of radioactive phosphorus.

The element phosphorus has atomic number 15; that is, it has 15 protons in the nucleus, and therefore 15 extra-nuclear electrons. Phosphorus has but 1 stable isotope occurring in nature. This has an atomic weight of 31; hence the nucleus consists of 15 protons and 16 neutrons. We can make a new and unstable type of phosphorus by adding 1 neutron to the nucleus. This can be realized most efficiently by bombarding ordinary phosphorus with deuterons. The nuclear reaction which takes place is indicated schematically in figure 4. Here we see a deuteron bombarding a phosphorus nucleus, and combining momentarily with it to form an unstable composite. This breaks up almost instantaneously with the emission of a proton, thus leaving the final heavy nucleus with 1 more neutron than is contained in ordinary stable phosphorus. This new product is radioactive phosphorus and has an atomic weight of 32.

On examination of the stable isotopes we find that a stable configuration of 32 particles exists in nature as an isotope of sulphur, which is atomic number 16 and therefore has 16 protons in the nucleus. It is evident that if 1 of the neutrons in the heavy radioactive phosphorus could transform itself into a proton, it could then realize stability, because the new nucleus so formed would be identical with one of the known stable iostopes of ordinary sulphur. This is exactly what happens. One of the neutrons in the nucleus of radioactive phosphorus changes into a proton. The fundamental physical laws of conservation hold among nuclei, and consequently at the same time that 1 unit of positive charge is created in the form of the new proton, 1 unit of negative electrical charge must also be created. Thus there is produced at the boundary of the nucleus a new electron, and this electron is fired away from the nucleus with great velocity because of the excess energy which is released from the nucleus as it becomes more stable in becoming sulphur. This rapidly moving electron is the beta ray.

The time delay between the formation of a radioactive nucleus and its decay depends upon the details of the nuclear configuration, and varies from one radioactive substance to another over extremely wide limits. In the case of radioactive phosphorus 35 out of every million such nuclei undergo the spontaneous transformation to stable sulphur each minute. This is equivalent to saying that half of any given initial stock of such radioactive atoms will remain unaltered for 14 days. The rapidity of decay of any radioactive substance is expressed by the time required for half of any initial stock of such atoms to decay; thus the "half-period" for phosphorus is 14 days.

The beta ray which is shot out from the decaying radioactive nucleus has a velocity very nearly equal to that of light, and in the case of radioactive phosphorus these electrons have kinetic energies up to 1,700,000 electron volts. These electrons are slowed down and eventually stopped by their passage through matter, in which they collide with the atomic electrons of the atoms through which they pass. Following some 50,000 such collisions, in each of which the atom struck is ionized, the beta-ray electron finally comes to rest. Then in the long run of

nature's averages this electron can be thought of as eventually rejoining the sulphur atom which was produced at the moment that the beta-ray electron was produced and expelled from the radioactive phosphorus nucleus. This new sulphur atom, having 16 protons in the nucleus, requires 1 more electron than was required by its parent, radioactive phosphorus. It can be seen that this extra electron is available, so that radioactivity never produces an unbalance between the number of protons and atomic electrons available in nature for the formation of neutral atoms.

A large number of radioactive transformations, but not all, yield a final nucleus which is not quite in its most stable state, and which almost immediately settles down into its most stable or "ground state" by the emission of additional energy in the form of a gamma ray. The energy of these gamma rays is just sufficient to take away the extra energy available in the nucleus, and the physical properties of the gamma ray are exactly the same as those of X rays of the same voltage. That is, the gamma ray is an electromagnetic radiation of high penetrating power which eventually loses its energy by producing ionization. This ionization process consists of the violent removal of an atomic electron from an atom in the absorber. The secondary high-speed electrons produced by gamma-ray or X-ray absorption are identical in their physical and biological properties with the beta-ray electrons from radioactive substances.

DETECTION

Where relatively strong radioactive sources are available, a simple ionization chamber and electrometer, or an electroscope, are satisfactory for observing the integrated ionization produced by a large number of beta rays. Where the highest sensitivity is required, discharge-counters, such as the Geiger-Müller counter, may be used to count the individual beta-ray electrons one by one. These electrical detecting devices are capable of producing an electrical pulse of any desired voltage for each beta-ray electron which passes through the sensitive volume of the counter. Although it has many variations, the discharge tube-counter usually consists of a cylindrical cathode and an axial fine wire anode, sealed into a glass envelope containing dry air or another gas at a pressure of about one tenth of an atmosphere. When a carefully regulated d-c potential is connected across the two electrodes, a voltage can be found where no discharge takes place through the tube until a single free electron enters the volume between the anode and the cathode. Then a momentary electrical discharge takes place between the electrodes, and immediately is quenched. This individual discharge can then be amplified with the aid of vacuum-tube circuits designed especially for this purpose. The output of such an amplifier consists of a series of pulses which are randomly spaced in time, since radioactive disintegration follows the usual statistical laws for a random process. Then one either can record the number of pulses directly on a tape or a message register, or, for higher counting rates, a vacuum-tube scaling circuit can be placed between the output of the amplifier and the message register. Greater convenience of operation, coupled with retention of the highest possible accuracy, is obtained by feeding the series of randomly spaced pulses into a capacity-resistance tank circuit and observing the relatively steady current thus produced in the tank-circuit resistance, which is the operating principle of the counting-rate meter.[8]

Counters designed for the observation of alpha rays or beta rays must be provided with a sufficiently thin window so that the ray can penetrate the window and enter the sensitive volume between the electrodes of the counter. Where gamma rays are to be observed no such window is needed, because the very high penetrating power of the gamma rays allows them to pass through the walls of the counter and to produce, directly in the sensitive volume, a free secondary electron, through the ionization of one of the atoms in the electrodes or the filling gas.

TRACER APPLICATIONS

Bearing in mind that the chemical properties of an atom are determined by the behavior of its outermost electrons, we are not surprised to find that the biochemical behavior of a radioactive substance is identical with the behavior of the stable isotopes of the same element. Thus to all ordinary chemical, physical, or biochemical systems ordinary phosphorus and radioactive phosphorus are indistinguishable, as are ordinary iodine and radioactive iodine, and similarly for all the other elements. Once they have been mixed together, it is impossible to separate by ordinary chemical or biochemical processes the stable from the radioactive atoms of any given element. It may be said that the electrons in any given atom do not know whether their nucleus is radioactive or stable, for this secret is locked in the heart of the nucleus.

We have said earlier that in the process of atom smashing the light and relatively remote atomic electrons have to get along as best they can while the violent collision between two nuclei takes place. It is no surprise that this collision shatters all chemical bonds, and that the new radioactive atom is formed as a free atom, rather than remaining in chemical combination as part of a molecule in the target. These atoms must then be taken by the radioactive chemist or the biologist and synthesized into whatever substances are of interest in the particular study at hand. Thus one cannot produce radioactive hemoglobin by bombarding the red blood cells with deuterons in the hope of making the iron which they contain radioactive. Instead, one must take iron as a target and bombard it with deuterons to produce radioactive iron. From such a bombarded target one atom in every million million may be successfully transmuted into radioactive iron, just as radioactive phosphorus is formed in the case used as an example earlier. This mixture of stable and radioactive iron atoms can then be converted chemically to ferrous sulphate. Then if this ferrous sulphate, containing radioactive iron, is fed to anemic dogs, it will be absorbed, and the new red blood cells which are formed later will contain hemoglobin made with radioactive iron. The utilization of the iron administered in such an experiment can be readily traced in all of its details by observing, with

counters, the radioactivity of samples taken from the blood and various parts of the body. Since the radioactive and normal atoms of iron are inseparable chemically they will retain a constant proportionality to one another during the entire subsequent history of the iron sample. Thus the radioactive atom acts as a tracer which allows one to locate the stable but chemically identical atoms with which it was originally mixed.

The use of tracer isotopes is one of the most widespread modern applications of nuclear physics. The method of radioactive indicators was a natural development from Madame Curie's initial radiochemical work, during the experiments on the discovery and separation of polonium and radium. As early as 1913 Paneth and Hevesy made the first applications of this method to chemical problems. During the years that followed they and their students made extensive investigations of the mechanism of exchange reactions, of oxidation-reduction couples, self-diffusion in lead, the metabolism of plants and animals, and many other problems in chemistry and biology. Thus the groundwork and the fundamental principles of the method of tracer isotopes all were well worked out long before 1930. There were severe limitations on this early work because only the naturally radioactive isotopes were available, so the tracer experiments could only be done on lead (with radium *D*), bismuth (with radium *E*), and thallium (with actinium *C″*).

The use of isotopes as tracers became a major field of applied nuclear physics during the middle and late 1930s. Only then were tracer isotopes of all the chemical elements discovered and made available in quantities, together with the means for detecting them. Now more than 350 radioactive isotopes of all the known stable chemical elements are known.

The present general usefulness of the tracer method therefore finds its origin first in the discovery of artificial radioactivity by the Curie-Joliots in 1934; second, in the perfection of the cyclotron by Lawrence and his collaborators, which provided very strong sources of these new radioactive substances; and third, in the development of detection instruments, based on previous developments in other fields of radioactivity.

Assumptions. In the use of isotopes for indicators it is assumed that the atomic-weight difference between the marked and the ordinary isotopes in any particular element is indistinguishable to the chemical, physical, or biological system being studied. This assumption has been checked many times by measurements of the specific radioactivities, where radioactive tracers are used. Especially pertinent is the determination by Schoenheimer and Rittenberg of the relative abundance of the stable nitrogen isotopes, which is found to be the same in amino acids, proteins, and air. Similarly, Dole has shown that the ratio of the hydrogen isotopes is the same in honey, cholesterol, benzene, and water. Thus the biochemical reactions in which these substances are formed do not distinguish between the isotopes of different atomic weight, even in light elements where the fractional differences in weight are largest.

When radioactive isotopes are used as biological tracers, one must add the condition that all doses be kept sufficiently small so that the presence of beta rays and any other radiations from the radioactivity in the organism will not alter the physiological process being studied. Radiation effects must be studied in separate control experiments and all doses kept well below the measured threshold for physiological effects. This threshold varies considerably. For example, in the study of phospholipid metabolism in mice, a total dose of about 36 microcuries* of phosphorus per mouse may be used if only the brain is to be studied, but this dose will alter the metabolism in other parts of the body. If blood and muscle metabolism are to be studied, only 16 microcuries of phosphorus may be used, while for liver studies only 8 microcuries are allowable. The doses must be even smaller for chromosome work, because 30 per cent of the chromosomes will be broken by a dosage of only 8 microcuries per mouse.

It may be pointed out again that the radioactive tracer atom is perfectly normal until the radioactive transition occurs. Until its disintegration a radioactive isotope is indistinguishable chemically from other isotopes of the same element. For this reason it is sometimes preferable to speak of the method of radioactive "spies", since the words "tracer", "tagged atom", and "marked atom" connote the existence of a difference between the isotopes which is not actually present. The radioactive isotopes are actually used as spies which go around unrecognized in the company of normal atoms of the same chemical type, and at a later time reveal the detailed movements of the normal atoms which they accompany. Ordinary experiments employ one spy atom for each 10^{10} to 10^{15} normal atoms whose course is to be traced.

Limitations. In considering the great merits of the method of isotopic spies or tracers, it is well to bear in mind also the limitations of the method. In the use of radioactive isotopes there are two principal limitations. First, the total amount of radioactivity administered in physiological experiments must be kept below the biological threshold. This imposes a limitation on the initial concentration that can be used, and hence on the maximum dilution that can be detected in any particular experiment. Difficulties from this source are usually not serious and almost always can be avoided by the use of highly sensitive detection apparatus. The second limitation is imposed by the periods of the radioactive isotopes, which are not subject to modification by man. Some elements have radioactive isotopes whose periods are too short to permit any but the simplest and quickest tracer experiments. Thus the radioactive isotopes of nitrogen have half-periods of only 8 seconds and 10 minutes, and these isotopes cannot be used for the study of intermediary metabolism of proteins. Fortunately an alternative isotopic tracer method based on the use of purified individual stable isotopes is available for nitrogen (and also hydrogen, carbon, oxygen, and sulphur). Excellent work on the intermediary metabolism of proteins and fats has been accomplished in this way.[9]

In the past two years great progress has been realized

* A curie of any radioactive element exhibits 3.7×10^{10} disintegrating atoms per second.

in the application of the spy method to problems in metallurgy, chemistry, and biology. Consideration of a few of the applications in biology will give a better understanding of the broad range of problems that can be attacked by this method.

Perhaps the most striking applications of the method of isotopic spies have been in the field of animal, plant, and insect physiology. This is because the method provides for the first time a means of studying the metabolism of various nutrients and toxins while the organism is in a normal, healthy, and equilibrium state.

Plant Metabolism. It has been found that plants are capable of effecting an exchange between the plant root and the very small colloidal clay particles of the kind found in the soil. Studies of this absorption process by a plant have shown for the first time that the nutrient positive ions can and do move in both directions between the roots and the clay particles.[10,11,12] Therefore the nutritional process of contact exchange must be divided into the two oppositely directed processes of contact intake and contact depletion of the root system.

The upward and lateral movement of salts containing potassium, sodium, phosphorus, and bromine has been studied in actively growing and transpiring willow and geranium plants. These experiments have shown conclusively that the path of rapid upward movement of salt is in the wood, or xylem, of the plant, rather than in the bark.[13] In addition to the rapid upward movement through the wood, there is a moderately rapid radial transfer from the wood to the bark.

With the aid of this new tool, plant physiologists are already making rapid progress in the determination of the rates of absorption, paths of movement, and distribution within the plant of nutrient elements.

Animal Metabolism. With the aid of radioactive iron the fate of iron atoms in normal and in anemic animals has been studied exhaustively by Whipple, Hahn, and their colleagues.[14,15] These experiments have disclosed a number of previously unknown facts concerning the metabolism of iron. In normal health the body clings very strongly to the iron which it contains, and absorption and excretion are extremely small. Rapid absorption of iron takes place in an anemic organism; that is, in one in which the need is great. Then the iron is absorbed almost exclusively from the gastrointestinal tract, and is transported by way of the plasma to the blood-producing centers, where it is made entirely into hemoglobin in a very short time. There is no direct exchange of iron between the hemoglobin and the blood plasma. New hemoglobin, containing radioactive iron, is detectable in the blood within about four hours, and the absorbed iron is made entirely into hemoglobin in from four to seven days in anemic dogs. The fractional uptake is found to increase as the size of the dose is diminished. Radioactive red cells readily may be removed from one animal and introduced into another. In this way the breakdown of red blood cells and hemoglobin can be studied quantitatively.

The thyroid gland plays fundamental roles in the regulation of growth and of body heat. Its hormonal secretions are rich in iodine, and the metabolism of this element, which appears to be of basic importance in the proper functioning of the thyroid, is being studied in several laboratories with the aid of radioactive iodine.[16,17,18,19] Both normal and diseased thyroid glands are found to take up iodine from the blood stream within a few minutes after administration. The uptake is very much greater in the case of an enlarged (hyperplastic) gland, while for both normal and hyperplastic thyroid glands the fractional uptake of iodine increases as the size of the dose is diminished. In human beings with toxic goiter, the thyroid gland will take up (figure 5) practically all of the administered iodine if the dose is of the order of 1 milligram or less. Basic studies are in progress on the rate

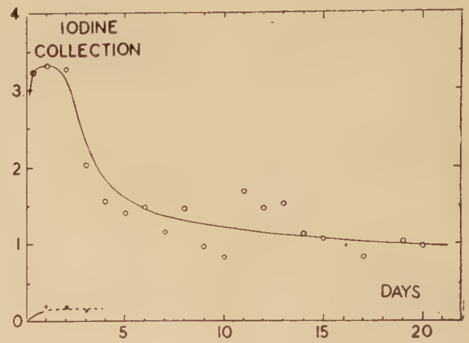


Figure 5. The upper curve shows the average uptake of iodine by the thyroid gland in six cases of human toxic goiter, following the administration of about one milligram of iodine containing radioactive iodine as a tracer. The lower curve shows the very much smaller accumulation in a normal human thyroid

and mechanism of the conversion of the absorbed iodine into the various chemical components of the hormonal secretions of the thyroid gland.

Vitamin B_1 has been synthesized, using radioactive sulphur, and studies of its storage, excretion, and utilization have shown that 10 per cent of the vitamin B_1 in the human body is destroyed every 24 hours.[20]

Using radioactive carbon, Hastings and associates have undertaken the study of carbohydrate metabolism. The formation in the liver of the important animal starch, glycogen, is found to involve a number of biochemical reactions the course of which could not be traced correctly by older methods.

All of these metabolic experiments, taken either individually or collectively, have disclosed extremely general, rapid, and widespread turnover and interchange among the molecules in the living body. Enzymatic equilibrium or steady state reactions occur everywhere all of the time in the body.

In summarizing the tracer work, it should be emphasized that the method of isotopic spies provides a unique method for investigating a normal animal or organism under equilibrium conditions. Calorie balance and nitrogen balance can be maintained rigorously during the entire course of the investigation. That this is a great step forward can be appreciated when it is realized that previous knowledge of intermediary metabolism usually had to come from experiments performed under wholly abnormal conditions. It was necessary to use organisms which were sick or poisoned, or from which certain tissues or

organs had been removed. Abnormal or unnatural compounds had to be administered, or diets unduly enriched or impoverished in the test substances employed. It is small wonder that the results of such experiments were necessarily fragmentary and often incompatible with one another. The entire field of physiology and biochemistry needs to be and is being re-examined with the aid of the powerful method of isotopic spies. In many cases the new results already obtained are contrary to previously accepted viewpoints. These new results serve to clear away much dead wood and to give valid reasons for discarding many alternative or conflicting interpretations of old observations. Fortunately the investigators have usually chosen to examine fundamental problems. Their new results are serving to establish a firm basis on which biochemical and physiological knowledge can be rapidly and consistently enlarged.

RADIATION THERAPY

The tools and the by-products of atom smashing have also provided several new agencies whose efficacy is being tried out in the field of radiation therapy. Fast neutrons were shown several years ago to have profound biological action. The usefulness of intense collimated beams of fast neutrons is being studied by Stone and his colleagues on more than 30 cases of cancer of the head and neck. While a number of cases have been treated, it is too early to draw any conclusions from this work. Fast neutrons penetrate tissue to about the same extent as 300-kv X rays. They produce biological effects which are roughly similar to those of X rays, but show several points of marked contrast. For example, skin reactions produced by fast neutrons both appear and disappear in a considerably shorter time than is the case for equally intense skin effects produced by X rays.

Studies of the therapeutic possibilities of slow neutrons were initiated by Kruger and have been continued by him and other workers. It is well known that both boron and lithium nuclei capture slow neutrons and that the resulting nuclear reaction liberates energetic alpha particles. Efforts are being made to localize molecules containing boron or lithium in tissues which it is desired to radiate. Since the probability for the capture of slow neutrons is much greater in the case of boron and lithium than for the other atoms present in the body, the radiation effects would be confined almost exclusively to the region in which the boron- or lithium-containing molecules had been localized. Difficulties in administering and preventing the diffusion of these materials must be overcome before the method can be used for therapy.

Wherever an artificially radioactive substance can be localized in a tissue which is in need of radiation, really selective interstitial irradiation can be readily administered by the use of the beta rays of very strongly radioactive materials. J. H. Lawrence and his colleagues have shown that phosphorus becomes concentrated in the bone marrow of human beings[21] and in the leukemic tissues in mice.[22] With this and other evidence as a basis, radioactive phosphorus administration has been tried as a possible therapeutic agent in some 75 cases of human leukemia. The results in cases of acute leukemia are not encouraging, but in the chronic leukemias further work seems certainly to be justified. Up to the present the results in many cases appear to be at least as good as those obtained by generalized X radiation of the patient. The administration of radioactive phosphorus can be by mouth, and is certainly much simpler and easier on the patient than the use of whole-body X radiation. Also, if such methods later become well standardized and generally accepted, they could be made readily available to patients in small towns, where expensive X-ray equipment is lacking.

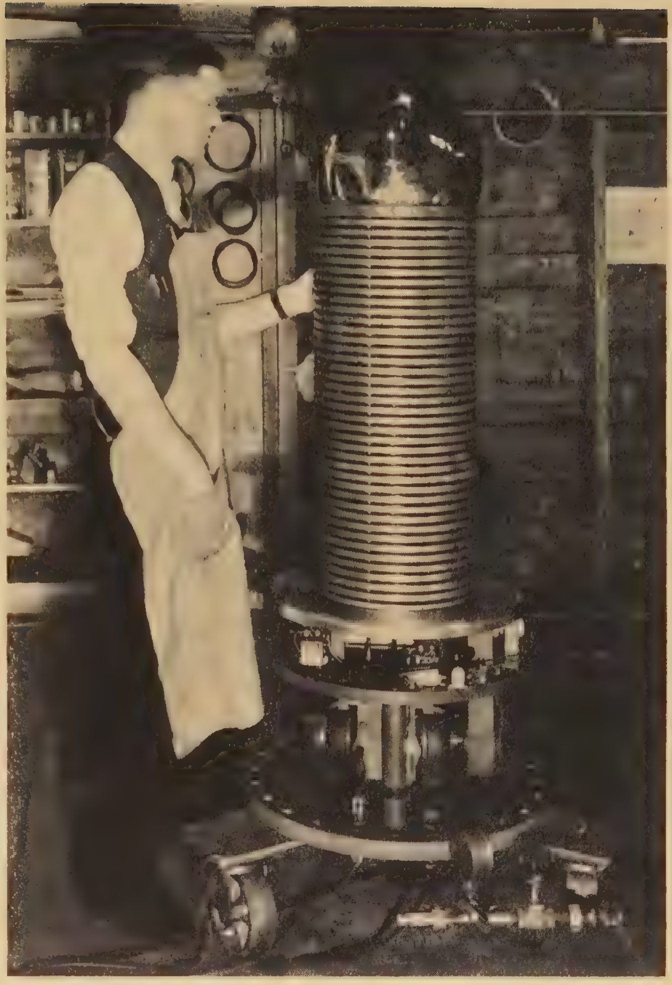


Figure 6. Interior of a new pressure-insulated electrostatic generator[25] at the Massachusetts Institute of Technology, for operation above 1,000,000 volts

Some of the machines originally designed for nuclear disintegration have been modified so as to be very effective X-ray generators. The Sloan high-frequency resonance transformer has been used for a number of years in two hospitals as a high-intensity X-ray generator[23] operating at about 1,250,000 volts. More recently Trump and Van de Graaff have extended the principles of the Van de Graaff electrostatic generator to produce very compact and efficient super voltage X-ray generators.[24] By the use of high-pressure Freon as an insulating gas, these workers have constructed successfully an X-ray generator which operates continuously at 1,200,000 volts and is completely

contained in a cylindrical tank 2 feet in diameter and 6 feet high. This generator operates at 0.5 milliamperes, and produces an intense radiation of 50 roentgens per minute as a distance of 70 centimeters, with 2 millimeters of lead and 5 millimeters of copper for filtration. A similar generator, to operate above 3,000,000 volts, is now nearing completion. The first 1,000,000-volt X-ray generator of the Van de Graaff type has given excellent hospital service for over 6 years.

These high-voltage generators also may be used for the production of intense and homogeneous beams of cathode rays.[25] These cathode rays have not yet been tested for therapy, but they give every indication of being useful in the radiation of surface malignancies. The depth of penetration of 1,500,000-volt cathode rays is about 8 millimeters in living tissue. Thus the use of cathode rays would permit expenditure of all the radiant energy in a relatively thin layer of surface material. The thickness irradiated can be regulated by adjustment of the cathode-ray voltage. Even with the use of very soft X rays, say 100 kv, so favorable a distribution of energy near the surface cannot be even approximated.

CONCLUSION

Radioactive forms (isotopes) of all of the known stable chemical elements now can be obtained by nuclear transmutation. These artificially radioactive atoms are useful as tracers, or spy atoms, to follow the movement and biological utilization of nutrients and toxins in normal animals and humans, even under equilibrium conditions.

Very strong sources of some artificially radioactive substances eventually may prove useful in radiation therapy. Some atom-smashing machines, when appropriately modified, are useful in metallurgical and clinical radiology.

REFERENCES

1. **W. H. Wells,** *Journal of Applied Physics,* volume 9, 1938, pages 677–89.

2. **F. N. D. Kurie,** *Journal of Applied Physics,* volume 9, 1938, pages 691–701.

3. **L. C. Van Atta, D. L. Northrup, C. M. Van Atta,** and **R. J. Van de Graaff,** *Physical Review,* volume 49, 1936, pages 761–76.

4. **E. O. Lawrence** and **M. S. Livingston,** *Physical Review,* volume 45, 1934, pages 608–12.

5. **E. O. Lawrence** and **D. Cooksey,** *Physical Review,* volume 50, 1936, pages 1131–40.

6. **M. S. Livingston,** *Review of Scientific Instruments,* volume 7, 1936, pages 55–68.

7. **G. T. Seaborg,** *Chemical Reviews,* volume 27, 1940, pages 199–285.

8. **R. D. Evans** and **R. L. Alder,** *Review of Scientific Instruments,* volume 10, 1939, pages 332–6.

9. **R. Schoenheimer** and **D. Rittenberg,** *Physiological Reviews,* volume 20, 1940, pages 218–48.

10. **H. Jenny** and **R. Overstreet,** *Proceedings* of National Academy of Sciences, volume 24, 1938, pages 384–92.

11. **H. Jenny** and **R. Overstreet,** *Journal of Physical Chemistry,* volume 43, 1939, pages 1185–96.

12. **T. C. Broyer** and **R. Overstreet,** *American Journal of Botany,* volume 27, 1940, pages 425–30.

13. **P. R. Stout** and **D. R. Hoagland,** *American Journal of Botany,* volume 26, 1939, pages 320–4.

14. **P. F. Hahn, J. F. Ross, W. F. Bale,** and **G. H. Whipple,** *Journal of Experimental Medicine,* volume 69, 1939, pages 739–53; volume 70, 1939, pages 443–51; volume 71, 1940, pages 731–6.

15. **L. L. Miller** and **P. F. Hahn,** *Journal of Biological Chemistry,* volume 134, 1940, pages 585–90.

16. **S. Hertz, A. Roberts,** and **R. D. Evans,** *Proceedings* of Society of Experimental Biology and Medicine, volume 38, 1938, pages 510–13.

17. **S. Hertz, A. Roberts, J. H. Means,** and **R. D. Evans,** *American Journal of Physiology,* volume 128, 1940, pages 565–76.

18. **J. G. Hamilton** and **M. H. Soley,** *American Journal of Physiology,* volume 127, 1939 ,pages 557–72.

19. **J. G. Hamilton** and **M. H. Soley,** *Proceedings* of the National Academy of Sciences, volume 26, 1940, pages 483–9

20. **H. Borsook, E. R. Buchman, J. B. Hatcher, D. M. Yost,** and **E. McMillan,** *Proceedings* of the National Academy of Sciences, volume 26, 1940, pages 412–18.

21. New International Clinics, **J. H. Lawrence, K. G. Scott,** and **L. W. Tuttle.** J. B. Lippincott Company, 1939, pages 33–58.

22. **J. H. Lawrence, L. W. Tuttle, K. G. Scott,** and **C. L. Connor,** *Journal of Clinical Investigation,* volume 19, 1940, pages 267–71.

23. **R. S. Stone, M. S. Livingston, D. H. Sloan,** and **M. A. Chaffee,** *Radiology,* volume 24, 1935, pages 153–9, 298–302.

24. **J. G. Trump, R. J. Van de Graaff,** and **R. W. Cloud,** *American Journal of Roentgenology and Radium Therapy,* volume 44, 1940, pages 610–14.

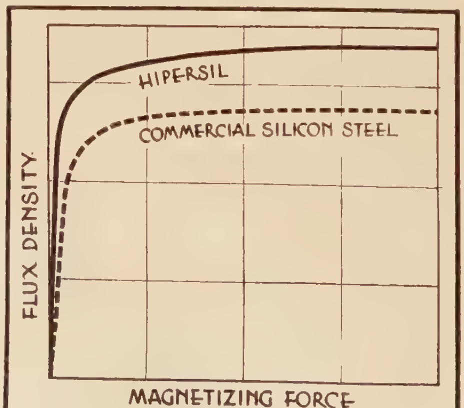
25. **J. G. Trump, R. J. Van de Graaff,** and **R. W. Cloud,** *American Journal of Roentgenology and Radium Therapy,* volume 43, 1940, pages 728–34.

An Improved Magnetic Steel

A NEW silicon steel having a magnetic saturation value approximately one third greater than conventional silicon steel has been announced by the Westinghouse Electric and Manufacturing Company. The new material, which has been named Hipersil (high-permeability silicon steel) reaches this higher saturation at the same magnetizing force as conventional silicon steel; its other characteristics are such that the core losses in transformers in which it is being used are no greater at the increased flux densities than they are in transformers using conventional steels.

The improved properties have been achieved by specially developed rolling procedure and heat treatment which produce in the final product a preferred orientation of the crystal lattice. For that reason, the material must be used in such a way that its "grain" is aligned with the direction of the magnetic field in order to take advantage of its improved properties; if the grain is at right angles to the field, its properties are inferior to those of ordinary silicon steel.

First application of the new material has been in distribution transformers in which size and weight have been reduced by as much as 25 per cent; use of the new material also has facilitated reduction of copper losses and thereby increased short-time overload capacities. Magnetostriction of the new material is reduced so that even at the increased flux density at which the material operates no increase in transformer noise results, as compared with transformers having cores of ordinary silicon steel.



Comparative magnetization curves of conventional silicon steel and Hipersil

Fluorescent Lighting Advances

Discussion at the technical session and conference on fluorescent lighting at the AIEE 1941 winter convention indicated that fluorescent lighting, introduced commercially only a few years ago, is rapidly advancing to a prominent position in the lighting art. Advances in the design and manufacture are resulting in better-quality lamps and equipment in a wider variety of sizes and ratings. Methods of application have been crude and unsatisfactory in many of the early installations, but correct methods are being developed and applied. These factors were among the principal subjects discussed at the session and conference mentioned; essential substance of the scheduled discussions is presented in the following pages. Advances in high-voltage fluorescent tubing and its application also were discussed at this conference. Essential substance of the scheduled discussion on this subject is planned for inclusion in a later issue.

Progress in Lamps and Auxiliaries

O. P. CLEAVER
ASSOCIATE AIEE

IT IS not unusual to hear the present referred to as the "era of fluorescent lighting," an optimistic description in view of the facts, for during 1940 some 600,000,000 large incandescent lamps were sold as compared to almost 9,000,000 fluorescent lamps. Fluorescent lamps, however, have showed phenomenal development in the three years they have been available for practical lighting application, and a growing public demand for them testifies to their satisfactory operation in service.

NEW FLUORESCENT LAMPS

To meet the ever-expanding fields of application for these lamps, new sizes have been introduced during 1940 and the first months of 1941. For convenience they may be divided into two classifications, those for general lighting services, and those for special lighting applications.

New Lamps for General Lighting Service. A 60-inch 100-watt fluorescent lamp (for technical data refer to table I) was announced in the early fall of 1940, making possible about $1^3/_4$ times more lumens per foot than are obtainable from the 40-watt lamp favored in the past for general lighting. Interest in the 100-watt lamp has been directed toward such applications as industrial lighting in RLM* reflectors, show windows, and continuous "troffer" lighting. Its length has not made it easily adaptable to fixture design and few have appeared as yet for general lighting purposes.

To meet the demand for a shorter lamp that would permit better-proportioned fixtures and still maintain a high lumen output per foot of lamp, the new 65-watt 36-inch fluorescent lamp was introduced in March 1941 (see table I).

Neither of these lamps is as efficient nor has as long life (2,000 hours in each case) as the popular 40-watt 48-inch lamp, yet they offer interesting possibilities for the future. Even though their bulb diameters are larger (T-17) than that of the 40-watt lamp (T-12), the brightness of the 100-watt and 65-watt lamp is slightly higher, being in the ratio of approximately 1 to 1.13, respectively.

New Lamps for Special Lighting Applications. Fluorescent lighting to date has not been used extensively in the home for many reasons, of which cost and fixture-design problems resulting from the shape and size of the lamp are especially notable. The introduction of the 14-watt 15-inch T-12 fluorescent lamp, so designed that it can be operated two in series with a small tungsten incandescent lamp as ballast (in series with the lamps) has resulted in

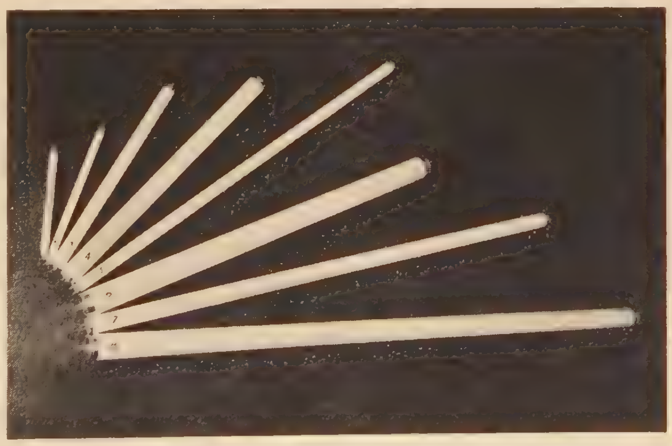


Figure 1. Standard fluorescent lamps as of March 1, 1941

1—6-watt 9-inch
2—8-watt 12-inch
3—15-watt 18-inch
4—20-watt 24-inch
5—30-watt 36-inch
6—65-watt 36-inch
7—40-watt 48-inch
8—100-watt 60-inch

O. P. CLEAVER is head of the illumination section, commercial engineering department, Westinghouse Lamp Division, Bloomfield, N. J.

*RLM—Reflector Lamp Manufacturers Association.

the introduction of floor lamps with this new fluorescent lamp replacing the customary candle-type filament lamps under the shade. Starting is accomplished manually by delayed switch action. The particular voltage characteristics of this lamp make it the only size that can be so operated.

Another short lamp introduced in 1940 has found some use in homes for bed lamps, decorative table lamps, and picture lighting. This is the small 6-watt 9-inch T-5 lamp available in white and daylight only. It has been applied in the commercial field for small display-case lighting, indicator lighting, airplane instrument-board illumination, and on business machines. Very recently, to meet similar applications requiring more light than is available from the 6-watt lamp, an 8-watt 12-inch T-5 lamp was made available (table I).

While fluorescent lamps may be many years in arriving at the variety of shapes and sizes now available in incandescent lamps (10,000 estimated), nevertheless in the short span of three years, additions to the original four lengths and two diameters have been sufficient to meet most application requirements. The trend in demand for the various standard lengths during 1940 is as follows:

Length	Watts	Per Cent* of Total
18	15	17
24	20	23
36	30	10
48	40	49
60†	100	1

Electrical Merchandising, January 1941.

†Introduced late fall, 1940.

NEW COLORS

The absence of the deep-red wave length in the spectrum of the white and daylight fluorescent lamps, and the presence of a mercury-discharge band spectrum superimposed upon the continuous spectrum obtained from activation of the phosphors, has caused some application difficulties where human skin, meat and vegetable displays, and certain other food displays are involved. Primarily to solve the meat-display problem, a new color has been introduced. Designated as "soft white", it also has proved a solution to many of the other color problems, since it develops a greater proportion of the red radiation than do the standard whites, and subordinates the yellow and green part of the spectrum. Department stores are using it in their women's clothing departments, and beauty parlors, night clubs, restaurants, and residences also are finding it satisfactory. This warmer color, however, is obtained at a lower efficiency—in the 40-watt size, the lumen output is approximately 30 per cent less than for the 3,500-degree white (see table I).

The fluorescent lamp was hailed by the illuminating engineer as a source which would produce colored light at very high efficiencies, thereby opening up many new decorative lighting fields. Statistics indicate, nevertheless, that the colored fluorescent lamps have declined in public demand in relation to the total number of lamps

Table I. Characteristics of the Mazda Fluorescent Lamp

Essential Technical Data

*Watts (Nominal—Lamp Only)	Bulb	Bulb Diameter (Inches)	†Over-All Length (Nominal—1 Lamp plus 2 Sockets) (Inches)	Base	Lamp Amperes (Approx.)	Lamp Volts (Approx.)	Rated Avg. Life**	Burning Position	*** Approx. Initial Lumens	
6	T-5	5/8	9	Min. Bipin	0.15	45	750	Any	3500° White	180
									Daylight	155
8	T-5	5/8	12	Min. Bipin	0.18	54	750	Any	3500° White	300
									Daylight	250
14	T-12	1 1/2	15	Med. Bipin	0.37‡	41‡	1,500	Any	3500° White	460
									Daylight	370
									Soft White	325
15	T-8	1	18	Med. Bipin	0.30	56	2,500	Any	3500° White	615
									Daylight	495
									Soft White	435
									Blue	315
									Green	900
									Pink	300
									Gold	375
									Red	45
15	T-12	1 1/2	18	Med. Bipin	0.33	48	2,500	Any	3500° White	615
									Daylight	495
									Soft White	435
									Blue	315
									Green	900
									Pink	300
									Gold	375
									Red	45
20	T-12	1 1/2	24	Med. Bipin	0.35	62	2,500	Any	3500° White	900
									Daylight	730
									Soft White	640
									Blue	460
									Green	1,300
									Pink	440
									Gold	540
									Red	60
30	T-8	1	36	Med. Bipin	0.34	103	2,500	Any	3500° White	1,450
									Daylight	1,200
									Soft White	1,050
									Blue	780
									Green	2,250
									Pink	750
									Gold	930
									Red	120
40	T-12	1 1/2	48	Med. Bipin	0.41	108	2,500	Any	3500° White	2,100
									Daylight	1,700
									Soft White	1,500
65	T-17	2 1/8	36	Mog. Bipin	1.35	50	2,000	Any	3500° White	2,100
									Daylight	1,800
100	T-17	2 1/8	60	Mog. Bipin	1.45	72	2,000	Any	3500° White	4,200
									Daylight	3,350

* For total watts add auxiliary watts.

†This dimension is the distance from the back face of one socket to the back face of the other using sockets of standard thickness. Sockets should be accurately spaced within $\pm 1/32''$ except $\pm 1/16''$ may be allowed for the 65- and 100-watt T-17 lamps.

‡Values apply when operated on standard 118-volt 15-watt ballast.

**Average life of lamps in burning hours under specified test conditions.

***Approximate lumens when measured at 80 F ambient and under specified test conditions. The light output of a new lamp will appreciably exceed the above published initial values which apply when the lamps have burned 100 hours.

With two 14 watt lamps operated in series with 60-volt 0.5-ampere S-11 resistance ballast lamp on 118 volts alternating-current—lamp volts 40, lamp amperes 0.39; on 118 volts direct-current—lamp volts 43, lamp amperes 0.33. (Note that starting difficulty may be encountered on direct-current if line volts fall below 110.)

sold. The trend in color demand during 1940 was as follows:

Color	Per Cent of Total
White	52
Daylight	43
Colors (Red, blue, pink, gold, green)*	5

*"Soft white" was introduced too late for inclusion in this table.

NEW AUXILIARIES

The year was not characterized by any such radical changes in auxiliary design as the separation of the ballast and the switch, which occurred during 1939. However, existing ballasts and switches have been improved by minor design changes and better manufacturing technique.

The acceptance of the two-lamp ballast has been most widespread, accounting for some 80 per cent of the total sales of ballasts today. Longer and more narrow two-lamp ballasts have been designed for the 40-watt and 30-watt lamps to permit their use in wiring channels and in continuous fixtures attached to ceilings and walls. Power-factor-corrected individual ballasts have been provided for all sizes of lamps to take care of applications where only one lamp or an odd number of lamps is required.

The glow type of switch is most universally used at present, but improved thermal types are available, indicating considerable progress in this field during the past year.

Experiments have been undertaken to arrive at a satisfactory solution of the radio-interference problem and at least two manufacturers have provided small inexpensive capacitors which may be attached directly to the fixture across the line. If the fixture is properly grounded, this method proves satisfactory in so far as line-feedback radiation is concerned.

IMPROVEMENTS IN LIFE, EFFICIENCY, AND COST OF LIGHT

Improvements in manufacturing technique and machinery for producing fluorescent lamps are also largely responsible for the remarkable advances made in life and efficiency of these lamps during the three years they have been commercially available. Starting in 1938 with a life span of 1,500 hours, today the standard lamps have life ratings of from 2,000 hours to 2,500 hours, depending on size and wattage (see table I). In that same time, the average efficiency in lumens per watt has increased nearly 40 per cent.

Price reductions also have been frequent, until the average list price today is about 65 per cent of that of two years ago. These price reductions, combined with longer life and higher efficiencies, make it possible to buy for a dollar in 1941 about seven times as many fluorescent "lumen-hours" (white and daylight) as in 1938, as shown in figure 2. Such improvements have greatly extended the fields of economic application for these new light sources, and are responsible in large measure for the steep slope of the ever-rising curve of fluorescent lamp sales.

Reliable estimates of the unit sales of fluorescent lamps expected by lamp manufacturers for 1941 are reported as ranging from 20,000,000 to 25,000,000. Such sales, combined with those of fixtures, ballasts, switches, sockets, wiring, and other equipment, would result in a $250,000,000 industry—that did not even exist three years ago.

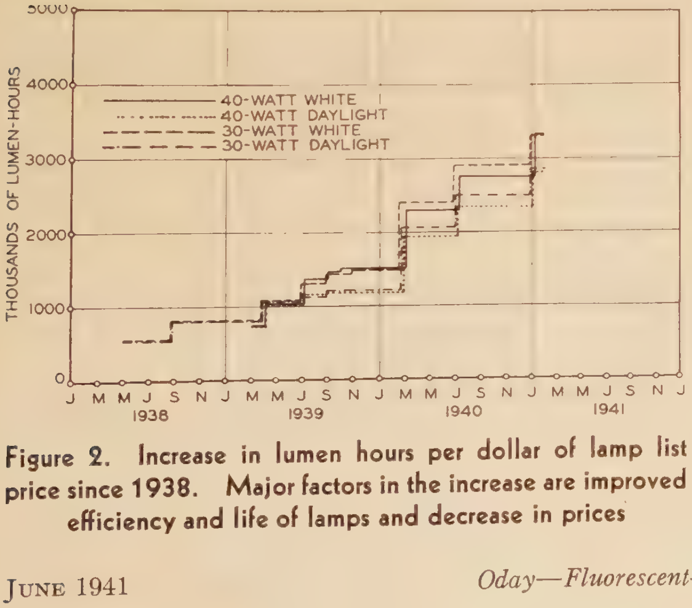


Figure 2. Increase in lumen hours per dollar of lamp list price since 1938. Major factors in the increase are improved efficiency and life of lamps and decrease in prices

Progress in Fluorescent-Lighting Equipment

A. B. ODAY

IN ORDER to get a better picture of the progress that has taken place with fluorescent-lamp equipment, it perhaps would be well to indicate where we started and how far we have gone since the fluorescent lamp first came into being. The fluorescent lamp first was made commercially available about $2^3/_4$ years ago. This new source was radically different in shape, size, method of operation, efficiency, brightness, and color quality from anything we ever had had before. We had little or no experience with sources of this type and therefore no precedents were available to help guide us. In $2^3/_4$ years the public has placed into operation between 8,000,000 and 10,000,000 of these new lamps. Considering that we started out with very little knowledge as to where, how, or in what quantity these new lamps would be used, I believe that it is not bragging too much to say that the industry has done a remarkable job.

It is of course easy to criticize what has been done and say that the mistakes were obvious and should have been avoided. Many have remarked that some early mistakes could have been eliminated if the introduction of these lamps had been delayed until a complete range of sizes and an adequate supply of well-designed lighting fixtures were available. A satisfactory answer to this criticism might be to remind the critics that lighting evolution has never been carried out on this basis. Most of the lighting

A. B. Oday is executive engineer, lamp department, General Electrical Company, Cleveland, Ohio.

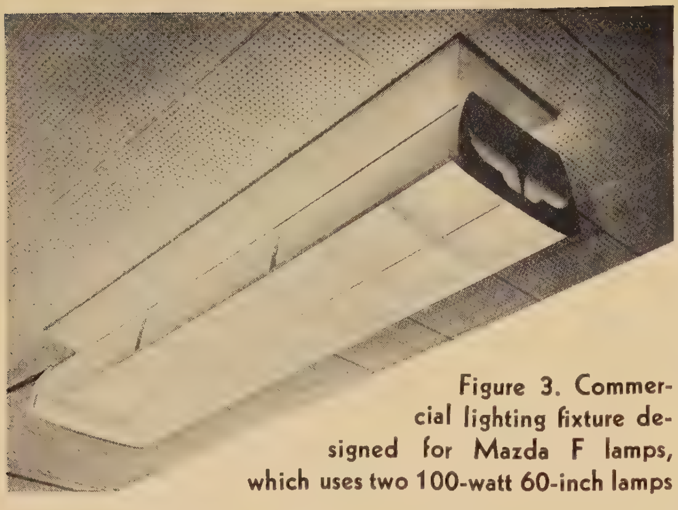


Figure 3. Commercial lighting fixture designed for Mazda F lamps, which uses two 100-watt 60-inch lamps

progress made to date has been built on practical experience. From experience we have found what not to do as well as what to do.

If the factors just mentioned are given due consideration one will agree that much of the early equipment, while inadequate in light of our present knowledge, was in reality about the most logical that could have been developed. In the year 1938, when fluorescent lamps were introduced, about all we had to start with toward a complete fixture, was a lamp, two sockets, an auxiliary, and a piece of wiring channel. The very first equipment was made up from these parts.

Many individuals have been prone to criticize manufacturers of lighting equipment. In my opinion severe criticism should be withheld, since they have developed lighting equipment on a basis that is usually considered logical. Certainly, in order to survey equipment needs to serve these new lamps, it was essential to estimate demands for new lighting equipment of different types, to make up suitable designs, to find money for tools to manufacture new equipment—during the early part of 1938 this in itself was not an easy task. Last but by no means least, time was required to start commercial production. While the permanently established manufacturers of lighting equipment were giving serious consideration to these requirements, many local metal-working plants assembled so-called lighting fixtures and peddled them to customers in their immediate neighborhoods.

All these early difficulties are recounted, not as an excuse for jobs done poorly, but rather as a background for the beginning of what eventually will prove to be a very important epoch in our lighting history.

Today in the early months of 1941 we can point with pride to real progress in the development of fluorescent-lighting equipment. If one considers only the availability of meritorious equipment, there is no excuse at the present time for the existence of poor fluorescent-lighting installations. Practically all the regular established manufacturers of lighting equipment are well prepared to serve the industry and the public.

In considering the progress we have enjoyed so far, mention should be made of the various specifications for fluorescent-lighting equipment that have been developed. These specifications include those pertaining to ballasts and starters, which make for adequacy of parts that are so essential to the proper starting and operation of lamps. Today such equipment is available carrying certification as to suitability to serve fluorescent Mazda lamps.

Specifications also are available covering the RLM types of industrial equipment. RLM labels on industrial equipment to serve fluorescent lamps indicate the same degree of excellence that the RLM label on other equipment has stood for over a period of years.

The Fleur-O-Lier label on fluorescent-lighting equipment indicates that such equipment has been submitted to an authoritative testing laboratory and that it complies with the specifications under which Fleur-O-Lier manufacturers operate. Some 40 or 50 manufacturers of equipment are now supplying such fixtures. Equipment complying with these specifications makes for a higher standard of merchandise and service.

It should of course be recognized that all equipment carrying labels is not necessarily of equal quality. It may not all be of the best possible quality, or all adequate for all uses. However, labels on equipment, whether it is ballasts, starters, or completed fixtures, give definite assurance that the equipment measures up to certain minimum standards of excellence in electrical characteristics, mechanical construction, and lighting performance.

From a very modest beginning, the progress in fluorescent-lighting equipment during the last two and three-quarters years has been such that the user now can get good equipment that will provide a sufficient amount of wattage to produce an adequate quantity of light in an interior; that will suitably distribute and control the light with a satisfactory minimum of brightness and glare; that is good mechanically and electrically, and, if appearance is a factor, is good to look upon. The fact that a generous assortment of lighting equipment incorporating all these essential characteristics is readily available in adequate quantity at reasonable costs indicates that the lighting-equipment industry has made very worth-while contributions, during less than three years, to the development of fluorescent lighting.

Survey of Fluorescent-Lighting Installations

PRESTON S. MILLAR
MEMBER AIEE

IT IS common observation that numerous installations of fluorescent lighting violate illuminating-engineering principles that have been built up arduously through the years. In many instances where competent design could have taken advantage of the higher efficiency of these new illuminants to produce excellent light-

PRESTON S. MILLAR is president, Electrical Testing Laboratories, New York, N. Y.

Table II. Average Data for General and for Supplementary Fluorescent-Lighting Installations

(Electrical Testing Laboratories)

	General Lighting						Supplementary Lighting			
	Food and Drug Stores	Jewelry Stores	Other Retail Shops	Restaurants	Offices	Industrial	Show Cases	Show Cases and Wall Cases	Booths and Windows	Overhead Lighting
Number of installations	14	4	50	12	37	11	5	9	4	9
Average total watts	1,443	2,382	3,980	1,797	5,790	7,760	2,863	1,022	692	688
Average hours per year	3,188	3,035	2,824	4,299	2,251	2,568	2,684	3,231	1,400	2,542
Power-factor distribution (Per cent of installations)										
Above 0.90	85.7	75.0	74.0	58.4	81.1	100	60.0	44.4	50.0	66.7
0.80 to 0.89	0	0	8.0	8.3	0	0	0	11.1	0	0
Below 0.80	14.3	25.0	14.0	25.0	18.9	0	20.0	44.5	50.0	33.3
No information	0	0	4.0	8.3	0	0	20.0	0	0	0
Lamp sizes, distribution (Per cent of installations)										
15-watt	19.8	22.5	3.0	11.2	1.3	0	31.6	12.8	22.0	11.5
20-watt	2.1	0	6.0	10.3	1.6	0	0.2	0.8	5.2	61.3
30-watt	3.8	34.1	10.1	46.9	32.7	0	68.2	69.9	52.0	20.7
40-watt	74.3	43.4	80.9	31.6	64.4	100	0	16.5	20.8	6.5
Color, distribution (Per cent of installations)										
White	37.5	39.0	59.5	44.0	58.8	4.6	93.4	32.1	0	25.8
Daylight	57.8	61.0	40.3	40.0	41.2	95.4	6.6	67.9	100	71.0
Others	4.7	0	0.2	16.0	0	0	0	0	0	3.2

Table III. Costs Involved in Fluorescent-Lighting Installations

(Electrical Testing Laboratories)

	General Lighting						Supplementary Lighting			
	Food and Drug Stores	Jewelry Stores	Other Retail Shops	Restaurants	Offices	Industrial	Show Cases	Show Cases and Wall Cases	Booths and Windows	Overhead Lighting
Number of installations	14	4	50	12	37	11	5	9	4	9
Average number of lamps										
15-watt	6.64	14.00	2.58	5.25	1.62	0	28.8	3.88	5.67	2.78
20-watt	0.71	0	5.24	4.83	2.05	0	0.2	0.25	1.33	14.78
30-watt	1.29	21.25	8.82	22.00	42.43	0	62.0	21.25	13.33	5.00
40-watt	24.93	27.00	70.46	14.83	83.59	158.4	0	5.00	5.33	1.56
Total	33.6	62.3	87.1	46.9	129.7	158.4	91.0	30.4	25.7	24.1
Average total watts	1,443	2,382	3,980	1,797	5,790	7,760	2,863	1,022	692	688
Average hours burned	3,188	3,035	2,824	4,299	2,251	2,568	2,684	3,231	1,400	2,542
Average cost of installation										
Lamps and equipment*	$313 (13)	$776 (3)	$1,065 (43)	$571 (10)	$1,443 (35)	$2,424 (10)	$148 (4)	$319 (9)	$155 (3)	$199 (7)
Wiring**	66 (*c*)	192 (*a*)	270 (*e*)	139 (*a*)	411 (*d*)	2,357 (*a*)	15	89 (*b*)	8 (*b*)	116 (*a*)
Total	$379	$968	$1,335	$710	$1,854	$4,781	$163	$408	$163	$315
Average per lamp per installation	12.28	14.02	14.23	16.21	14.32	28.02	10.17	15.12	8.77	17.54
Average annual cost of lighting*	$209 (14)	$774 (3)	$640 (47)	$335 (11)	$868 (35)	$790 (11)	$374 (5)	$133 (9)	$42 (3)	$167 (8)
Average cost per lamp	6.24	11.21	7.63	6.87	6.79	4.99	4.11	4.93	2.25	6.19

*Numerals in parentheses indicate the number of installations for which cost data were available.

**Letters in parentheses indicate the number of installations for which the wiring cost was given as zero. (*a*) = 1, (*b*) = 2, (*c*) = 4, (*d*) = 12, (*e*) = 15.

ing effects, incompetent design has resulted in unsatisfactory illumination. Evidently the novelty of fluorescent lighting has attracted into the lamp manufacturing and selling business many people who are not equipped by training and experience to deal competently with the subject.

In an endeavor to collect information concerning the few installations of fluorescent lighting that are regarded as satisfactory by people who are acquainted with them, Electrical Testing Laboratories in the summer of 1940 distributed to electric-utility men a questionnaire designed to bring out the qualities of such installations. The survey proceeded falteringly through several months. Correspondents in some parts of the country reported that they knew of no satisfactory installations. Elsewhere correspondents sent in data for a few that were reported to be fairly satisfactory. Correspondence back and forth regarding lacking or questionable details of the data submitted consumed so much time that, in view of the rapid advance in this art, the material finally summarized may be almost obsolete.

Originally it had been planned to classify the material in order to arrive at descriptions of representative satisfactory installations in various types of interiors. It developed, however, that diversity of characteristics was so great and numbers of installations of a comparable character were so small that it was necessary to consolidate the data for several types of installations.

Tables II, III, and IV present some of the data secured. Briefly, the result of this not very satisfactory survey

makes available the following information. It must be dated as of 1940.

Most of the installations utilized 40-watt lamps with 30-, 15-, and 20-watt lamps following in the order named.

"White" and "daylight" lamps were about equally divided, the so-called daylight lamps being more largely used in food, drug, and jewelry stores, while the so-called white lamps were used more largely in retail stores.

Daylight lamps found place generally in industrial installations, while in auditoriums, automobile showrooms, and so on, white lamps predominated. Only in restaurants were lamps of other colors used to any considerable extent.

Most of the luminaires reported upon were of the direct-lighting type. Only about 30 per cent were shielded to reduce the observable brightness.

In these better installations power factors of the equipments were usually more than 85 per cent lagging.

The most commonly cited advantage of fluorescent lighting was the higher lighting intensities made available.

The most frequently cited disadvantage was flicker of light, which apparently was applicable mostly to installations in which neither flicker nor power factor was controlled.

In about 50 of the installations reported upon, data of watts consumed afforded comparison of present fluorescent- with preceding incandescent-lighting installations. The watts consumed in the fluorescent-lighting installations averaged about 93 per cent of the number consumed in the superseded incandescent-lamp installations. The fact that the range was from 25 to 229 per cent offers abundant indication of the opportunity that exists for varying lighting installations to secure new and better results and also to allow them to drift into inferiority.

Average foot-candles of course afford only a crude indication of lighting results. For what it is worth, however, the average shown by this survey of the better fluorescent-lighting installations was about 26 horizontal foot-candles. In the installations in which the illumination was measured at point of utilization the average was approximately 40 foot-candles.

These indications of the 1940 status of fluorescent lighting in its better applications leave one with a feeling of dissatisfaction concerning the probable lighting conditions in the installations not included in this survey. This feeling of dissatisfaction is accentuated by common observation. There is a great need for more intelligent application of fluorescent lighting.

Applications of Fluorescent Lighting

ARTHUR A. BRAINERD

THE fluorescent tube has certain desirable characteristics not possessed by its predecessors. Fundamentally, it is a low-brilliancy, large-area source, and good diffusion may be secured without the use of elaborate equipment. For high-level, localized general illumination, or uniform general lighting where low ceilings prevail, these characteristics are desirable. However, the light flux from this lamp cannot be projected great distances without loss which more than counterbalances its inherently high efficiency. The fluorescent lamp has the further advantage of being able to create a reasonably accurate reproduction of daylight, a characteristic which is a necessity in many specialized operations. Furthermore, a wide variety of colors may be secured without the use of absorption screens. In some cases this means nearly 200 times the usable light per watt.

While each individual problem must be studied on its merits, there are certain conditions under which some form of fluorescent lighting is obviously the most logical solution:

1. Since it is a long light source, the shadows are not harsh when mounted near the work, and in many cases, hardly noticeable at all.

ARTHUR A. BRAINERD is director of the lighting service section, Philadelphia Electric Company, Philadelphia, Pa.

Figure 4. Fluorescent lighting is used for tubular knitting machines at a hosiery mill to secure 60 foot-candles of illumination with $3^1/_{10}$ watts per square foot

Table IV. Illumination Values

(Electrical Testing Laboratories)

	Installations in Which Foot-Candle Values Are Averages								Installations in Which Foot-Candle Values Are Known or Believed to Be at the Point of Utilization					
	No. of Instal-lations		Total Watts	Watts Per Sq Ft	Avg. Foot-Candles	Applied Lumens Per Watt	Total Installa-tion Cost	Cost Per Foot of Lamp Length	No. of Installa-tions		Total Watts	Avg. Foot-Candles	Cost of Instal-lation	Cost Per Foot of Lamp Length
Direct, exposed in both directions	28	Avg.	2,759	1.5	21	14.2	$ 648	$ 3.65	9	Avg.	4,658	51	$1,076	$3.57
		Max.	17,199	6.5	60	24.0	2,600	6.67		Max.	14,373	200	3,250	7.76
		Min.	159	0.4	2	5.0	33	1.77		Min.	588	15	165	1.95
Direct, exposed in one direction	15	Avg.	1,768	1.8	25	15.3	583	4.38	3	Avg.	3,087	30	850	3.22
		Max.	5,439	5.5	60	24.0	2,154	8.33		Max.	5,880	35	1,800	3.75
		Min.	160	0.5	11	10.9	100	2.54		Min.	736	24	200	2.55
Direct, concealed by glass	12	Avg.	5,544	2.2	32	14.0	3,073	4.80	5	Avg.	5,765	39	2,076	4.06
		Max.	20,825	5.2	85	19.2	16,565	9.34		Max.	11,779	60	6,000	6.29
		Min.	592	0.8	8	10.0	180	2.55		Min.	784	30	180	2.71
Direct, concealed by louvers	6	Avg.	5,562	2.7	34	13.3	2,023	3.60	1	Avg.	4,508	42	1,650	4.48
		Max.	19,600	4.3	41	15.8	8,200	5.16						
		Min.	1,176	1.8	24	7.0	210	2.05						
Direct indirect, exposed in both directions	3	Avg.	2,965	2.2	27	12.4	712	2.93	1	Avg.	2,671	25	623	2.60
		Max.	5,488	2.5	40	17.4	1,340	2.99		Max.	4,704	35	1,080	2.81
		Min.	760	1.7	20	8.0	185	2.83		Min.	1,568	15	340	2.34
Direct indirect, exposed in one direction	4	Avg.	1,544	2.4	35	14.8	362	3.15	0					
		Max.	2,156	4.3	65	17.7	535	4.33						
		Min.	490	1.3	20	12.0	173	2.33						
Direct indirect, concealed by glass	4	Avg.	4,688	1.7	20	10.9	977	7.86	0					
		Max.	9,016	3.4	45	13.2	2,105	16.67						
		Min.	444	0.9	8	8.9	227	2.86						
Direct indirect, concealed by louvers	6	Avg.	3,446	2.6	33	13.6	1,071	3.97	1	Avg.	1,764	45	500	3.47
		Max.	10,976	4.4	45	23.5	3,500	6.10						
		Min.	392	1.7	15	5.2	100	2.34						
Coves	13	Avg.	3,194	1.7	11	6.0	1,211	5.21	0					
		Max.	10,804	3.3	35	12.9	3,833	7.19						
		Min.	862	0.4	2	2.1	375	3.17						
Combination of direct and indirect, concealed by glass	1		39,113	2.6	36	13.8	12,000	3.78	0					

This is especially valuable where a workman's hands and body are continuously casting grotesque shadows under other systems.

2. The brightness of a 40-watt white tube is of the order of five candle-power per square inch. While this is too bright to be used in the direct line of vision, it is only a small fraction of the brightness of an incandescent filament or mercury vapor arc, and the direct reflections from polished surfaces are so low in brightness that even if these reflections do hit the eyes, the discomfort is negligible compared with that caused by other sources. In many cases, lighting levels of 100 to 200 foot-candles are required for seeing tasks of unusual severity. This requires relatively low hanging units of high lumen output. Fluorescent lighting, because it projects far less radiant heat, can provide such illumination quite comfortably.

3. Its characteristic high efficiency, coupled with the fact that it can be operated equally well on 110 or 220 volts, frequently make possible major improvements without an expensive rewiring job.

4. Where long burning hours are the general rule, the long life of the fluorescent tube is a distinct asset. Tubes operated continuously rather than intermittently usually will continue to give service far beyond their rated life.

5. Since this lamp is available in a variety of colors, interesting new decorative effects are now possible which were both difficult and expensive to secure with older sources.

6. The ability to approximate daylight in color quality is valuable, not only in operations where color must be identified, but also in bridging over the transition from daylight to 100 per cent artificial light.

Against these advantages, consideration must be given to the following:

1. The equipment is heavy and bulky, usually requiring supports at two points. Bulky equipment is sometimes objectionable from the standpoint of appearance, and in low-mounted localized systems may interfere with the work to be done.

2. Light fr om a fluorescent source is difficult to project any great distance and its light can never be concentrated in a small spot.

3. A multiplicity of low-output lamps increases the cost of maintenance. The problem of keeping lighting units free from dust is frequently serious and because of the long life of the fluorescent lamp, maintenance must be scheduled at regular intervals rather than cleaning only when lamps are replaced. It is never advisable to wait for a burnout before cleaning the reflectors.

4. At present, the cost of fluorescent equipment is rather high. This consideration, however, undoubtedly will become less weighty as the acceptance of this light source becomes more general.

INDUSTRIAL SEEING TASKS

The purpose of any industrial lighting installation is to enable the workers to see quickly, comfortably, and accurately. The primary object is strictly utilitarian, and pleasing appearance, while desirable, is a consideration decidedly secondary to the ability to produce favorable seeing conditions continuously, with minimum cost of maintenance. Much as we might desire it, there is no one best formula for good industrial lighting. Under certain conditions, as in textile work, shadowless illumination may be required; under other conditions, as in certain inspection operations, shadow or glint may be necessary. In a large foundry or assembly bay, uniform general illumination is the best solution, while in mass production assembly, high level localized lighting may be the only practicable solution. These are only a few of the many items which must be considered, and there is no one piece of equipment or light source which can reasonably be expected to solve all lighting requirements.

In all industrial lighting, the only illumination that

Figure 5. In the studio of a photoengraving company fluorescent lighting with continuous twin reflectors provides horizontal illumination of from 45 to 60 foot-candles

light fluorescent lamp, coupled with its low brilliancy, has proved a very acceptable and satisfactory answer.

High-Level Lighting for Fine Work. For many years we have known that lighting levels of 100 foot-candles and even higher were desirable for many delicate operations which place an unusual strain on the eyes. A degree of precision and accuracy in mass-production operations which was undreamed of a few years ago is now the accepted practice, and usually the seeing problem is one extending over long periods of time. Even the lowest-priced automobiles are constructed with tolerances of 1/1,000 of an inch or less. To provide the lighting levels necessary to carry on such fine work, some form of localized lighting is almost essential. Modern practice specifies a high level of uniform general illumination (at least 20 foot-candles), supplemented by a much higher level of lighting in the working area. For this supplemental lighting, a well-designed multitube fluorescent lighting unit offers a very satisfactory solution.

Other Localized Applications. For the localized lighting of woodworking machinery and machine tools such as lathes, drills, punch presses, millers, shapers, and boring machines, the new RLM fluorescent unit and several of the more specialized pieces of equipment give results that can be secured in no other way. White tubes used in connection with two-lamp auxiliaries reduce stroboscopic effect to a negligible value and thus contribute greatly to the safety of the worker. Where possible, such equipment should not be fastened to the machine, but rather suspended independently at a height that will not interfere with the workman. For the complete success of such an installation, only rugged equipment should be used, installed in such a way as not to detract from the appearance of the plant.

Imposing stones, folding and trimming, and proofreading areas, in the printing industry, have been successfully lighted. Problems of tobacco selection, cigarette and cigar manufacture, have been solved with the daylight lamp, usually through localized applications. Many installations of 40 or more foot-candles of general illumination for plant offices, file rooms, drafting rooms, and areas of like nature, are now in use.

counts in production is that in the working area, while work is being done—*light where you work, when you work.* Many work areas are long and narrow. Such areas are quite common in the various textile industries and include such operations as silk hosiery knitting, weaving, spinning, spooling, winding, quilling, beaming, etc. In most of these operations, seeing is on both the vertical and horizontal planes. In applications of this nature, what is needed is a long narrow wedge of light projected in the working area with enough spill light to eliminate dark areas at wide angles of vision. For such areas, fluorescent lighting is logical and satisfactory.

Bench work of all kinds constitutes another condition where the work area is long and narrow. A continuous line of fluorescent tubing produces a very satisfactory field of light in the business area without discomfort from projected heat or glare. Assembly lines, or production lines of mass-production items, are physically the same as bench work. Such areas usually require relatively high levels of light and freedom from heat and reflected glare. Typical of such areas are radio-assembly lines; cutting and sewing tables in the garment industry; inspection and packing in such industries as glass-bottle making and candy making.

Special inspection operations have always been a problem for the lighting engineer and each one must be considered on its merits. Where color determination of textile fabrics or other manufactured products is involved, north skylight has been the standard for many years. In a large percentage of these cases, where daylight fluorescent lighting has been tried, it has proved satisfactory. However, the acceptance has not been unanimous.

For determining physical defects in woven fabrics, scribe marks on metal, defective workmanship in small metal parts, etc., the characteristic spectrum of the day-

APPLICATIONS FOR WHICH FLUORESCENT LAMPS ARE NOT SUITABLE

While it is inevitable that there should be border-line cases, there are certain industrial applications where, because of certain inherent qualities in the lamp itself, fluorescent lighting is not the best solution.

High Mounting Conditions. The most conspicuous illus-

tration of this point is the matter of lighting areas where, because of the nature of the operation, all lighting equipment must be mounted a considerable distance above the working plane. Such conditions obtain where traveling cranes or overhanging machine projections, which must be adjusted from time to time, and fabrication and assembly operations interfere with low hanging equipment. For such conditions, relatively few pieces of lighting equipment, each equipped with a high-power concentrated light source, furnish the most satisfactory solution. It is quite probable that where the mounting height exceeds 12 to 14 feet above the floor, the advantage of efficient redirection, plus the lower maintenance of 10,000-, 20,000-, and 30,000-lumen lamps, would indicate that the incandescent lamp or the high-pressure mercury tube will provide the most satisfactory solution of the problem.

Congested Areas. Another very definite handicap of present fluorescent equipment is its physical size. A 10,000-lumen (500-watt) incandescent Glassteel unit, for example, is only 20 inches in diameter and takes up only 2.6 square feet of area. To provide the same illumination from fluorescent sources would require five 40-watt white tubes. A two-tube (4,100 lumen) RLM unit takes up 6 square feet of area. In other words, the fluorescent equipment could be expected to take up at least five times as much space as the Glassteel for the same light output. For this reason, where machines have low projecting parts, or where the drive is by belt and line shafting, fluorescent lighting cannot be satisfactorily applied.

Dusty, Damp, and Hazardous Locations. Open fluorescent units, either for general or localized use, should not be used where dust and dirt will speedily impair their efficiency; and where dust or vapor explosive hazards exist, fluorescent lamps cannot be used, since no equipment meeting Class 2G, 2F, or 1D, hazardous locations, is available today.

COMMERCIAL APPLICATIONS

The term "commercial" as applied to lighting, includes both offices and sales areas. In contrast to industrial lighting with commercial lighting, favorable appearance is as important as easy, rapid, and accurate seeing.

As in industrial lighting, so in commercial lighting, there is no sure cure for all diseases. Under certain conditions as in show cases, heat characteristics alone confine the field almost exclusively to fluorescent lighting. For spot lighting displays in show windows, however, only a concentrated source such as the incandescent lamp can be logically considered. In between these two extremes are a multitude of locations where the choice is by no means self-evident. However, there are two general rules which must always apply:

1. The lighting system must provide comfortable and rapid seeing
2. It must harmonize with its immediate surroundings.

In many commercial areas shadowless illumination from extended light sources is desirable, and projection of light is not involved. Frequently, a color approximating daylight is invaluable, and splashes of colored light constitute a distinct decorative asset. Under such conditions fluorescent lighting may be a logical and highly satisfactory method of producing the desired results.

General Lighting of Sales Areas. While the most effective way of utilizing the fluorescent light is in continuous lines, there are many satisfactory multitube fluorescent units on the market which produce quite a satisfactory seeing result when mounted on correctly spaced outlets. Since the trend in commercial lighting is toward continually higher levels, it is by no means good business to utilize the higher efficiency of the fluorescent lamp to lower the electric bill. A modern four-tube 200-watt commercial unit gives out approximately 8,500 lumens as compared to 10,000 lumens for a single 500-watt filament lamp. This fact should be taken into consideration in determining the spacing. The most effective general lighting with fluorescent sources can be done when it is built into a room in continuous lines.

Because of its low temperature, fluorescent lighting is almost ideal for show-case lighting, although in certain isolated cases color distortion and fading have been reported.

Daylight fluorescent lamps have become quite popular for fitting mirror and color-matching purposes and probably

Figure 6. A men's clothing store uses fluorescent lamps mounted and built in porcelain enamel units, and providing 85 foot-candles of illumination when installed

should be used for all except the most critical color-matching requirements. Garments that are to be worn in the evening should, of course, be displayed under incandescent light.

For silhouette signs and local display identification fluorescent lighting is almost ideal, because of its size. It produces very uniform results.

For all except very low-ceilinged show windows, the filament lamp continues to be the basic light source. The fluorescent lamp, if used at all, should be for producing a general flood of light and should be augmented by filament lamps in suitable projection equipment. Frequently, silvered reflector lamps in combination with fluorescent lamps insure a happy solution of the show-window lighting problem.

Office Lighting. This class of lighting falls under two general headings. The first and most extensive is the lighting of large office buildings. Where the ceilings are low, fluorescent lighting has a distinct advantage over the filament lamp, particularly where the wiring is inadequate for high-level incandescent lighting. Here the high initial cost of fluorescent equipment may be largely offset by the decreased cost in wiring changes. Moreover, fluorescent lighting equipment can be mounted close to the ceiling or even countersunk flush with sound proofing, thus producing a more spacious effect.

However, modern incandescent luminaires produce fully as satisfactory illumination with much less equipment to maintain. Office luminaires are now available using the 750-watt and 1,000-watt bi-post incandescent lamp which produce excellent illumination without glare, even on very low ceilings. Such practice insures a minimum of maintenance expense. Indirect luminaires using silvered bowl lamps are also quite effective and have the added advantage that every lamp replacement means a brand new reflector.

The choice of a lighting system for office-building service calls for an accurate analysis of fixed and operating costs of both systems. In the case of rentable offices the novelty of fluorescent lighting may be a strong enough factor in attracting new tenants to justify the initial capital investment and increased maintenance.

For small offices attached to stores or industrial plants, fluorescent lighting has certain distinct advantages where ceilings are broken up by steam pipes or other obstructions which prevent any satisfactory lighting installation with indirect or luminous indirect incandescent systems. Where such obstructions do not exist, the choice of a fluorescent system would be largely one of personal preference.

A SPECIALIZED SEEING TOOL

To sum up the situation, the fluorescent lamp is one of three generally available modern artificial light sources which has certain characteristics not possessed by either of its competitors. Fluorescent lighting should not be considered at the present time where light must be projected over 12 or 14 feet; where a concentrated spot of light is required; or where, because of its physical size, it becomes an obstruction. There are many seeing problems which can be very readily solved with fluorescent lighting, concerning which there is little doubt as to choice. There are also many other seeing tasks which can be satisfactorily solved with incandescent or high-pressure mercury lamps, as well as with fluorescent. In some cases a combination of two different light sources offers a logical solution. The ultimate choice will depend upon the personal preference of the buyer. Lastly, there are some seeing tasks for which fluorescent lighting is quite unsuitable, and for such locations it should be very definitely ruled out.

The fluorescent lamp is without question the most efficient light source available today, if we consider only the number of lumens emitted per watt, but we should not forget that the purpose of a lighting system is to produce not only light, but the best possible seeing conditions for the task at hand, with a minimum of operating and maintenance expense. Unless these conditions are produced, no lighting system can be described as efficient, and the cost of installation and operation of any lighting system will be satisfactory only when the special advantages of the light source are applied as a solution to the work problem involved.

When used for localized lighting at mounting heights of 2 to 5 feet over the working area, fluorescent lamps of the 30- and 40-watt sizes should be used with a minimum of 2 watts per square foot, and 3 to 5 watts per square foot will produce 50 or more foot-candles for very satisfactory performance. For general illumination the longer more efficient tubes should be used and $1^3/_4$ watts per square foot, or more, has provided seeing results that have inspired unusually favorable comment. These values are to be considered as present-day minimums and frequently much more illumination can be used with profit.

Multiple-lamp units eliminate stroboscopic effects when two-lamp auxiliaries are used and power factor is raised to near unity. Definite consideration must be given to high-power-factor equipment if penalties are to be avoided and if full efficiency of the wiring system is to be obtained. High-power-factor reactors are available, or corrective equipment in the form of capacitators may be used to bring the system to 90 per cent power factor, and such equipment should be installed.

While fluorescent lighting is here to stay, the other light sources have a definite place in industry and will probably continue to be used for many years to come. For this reason, before making any major changes in an industrial lighting system, it is advisable to compare the characteristics of the various light sources available and make the final selection on the basis of ability to create the best seeing conditions.

Industrial lighting is now in a transition stage in which new discoveries and new methods are continuously being made available. At such a time it seems rather trite to say that rapid obsolescence is the order of the day. The danger is not that we may adopt something wrong, but rather that, in our eagerness to be up to date, we may expect too much improvement from a poorly planned and inadequate fluorescent system.

Calculation of Fault Currents in Industrial Plants

RAYMOND C. R. SCHULZE

A detailed example illustrates the application of a method of calculating fault currents, knowledge of which becomes increasingly important as the rate of industrial expansion accelerates

THE calculation of fault currents at low voltages has been, until recently, a somewhat neglected subject. No new theory or practice is involved, but two things are necessary: an understanding that *all* parts of the system must be included at low voltages, and the extension of tables and curves to include the conductor sizes and configurations found at low voltages. For example, at 220 or 440 volts, even a ten-foot section of bus will have some bearing on the magnitude of the short-circuit current. Therefore, it is important that everything be included in the final reactance figure. Furthermore, the information should be put into a form which is easily understood.

This article is one attempt to solve these problems. The data have been put into a convenient form, and the sample problem gives the reasoning concerned with the various steps, as well as the calculations themselves.

Faults can be divided into four groups. The relative values of fault current are:

Short circuits

Three phases to ground or free of ground....................1.00
Between two-phase wires, no ground........................0.87

Grounds—with solid neutrals

One phase to ground or two phases to ground:
Impossible to give any general rule.
At neutral-grounded transformer.......Probably more than 1.00
Some distance from neutral-grounded transformer..Less than 1.00

These figures are for comparative purposes only, and are intended to indicate that the three-phase fault current—the easiest one to calculate—will give a good idea of the magnitude of the current for any type of fault. Certainly a knowledge of the three-phase fault current is much better than none at all.

The calculations assume that:

1. A solid copper-to-copper connection exists between all phases at the point of short circuit. There is no allowance for arc or fault resistance.

2. The power supply is from a private utility system, so that the current value is independent of time (after the first few cycles). If the industrial plant has generators of its own, then the current will decrease as the time from the instant of fault increases, because of demagnetization of the plant's generators.

3. If fuses operating in one cycle or less are used, the value of current which the fuse may interrupt may be 1.73 times the value calculated here.

Only three-phase faults will be considered. They are the easiest to calculate, and they give an indication of fault conditions sufficient for most purposes.

The only equation necessary is Ohm's law

$$I = \frac{E_n}{X} \tag{1}$$

where

I = amperes per phase (same value in each phase).
E_n = volts from phase to neutral = 0.577 × volts from phase to phase.
X = ohms reactance, from the internal voltages of the generators, to the fault.

The determination of the value of X is the difficult part of setting up this equation.

The exact value of fault current will be obtained by

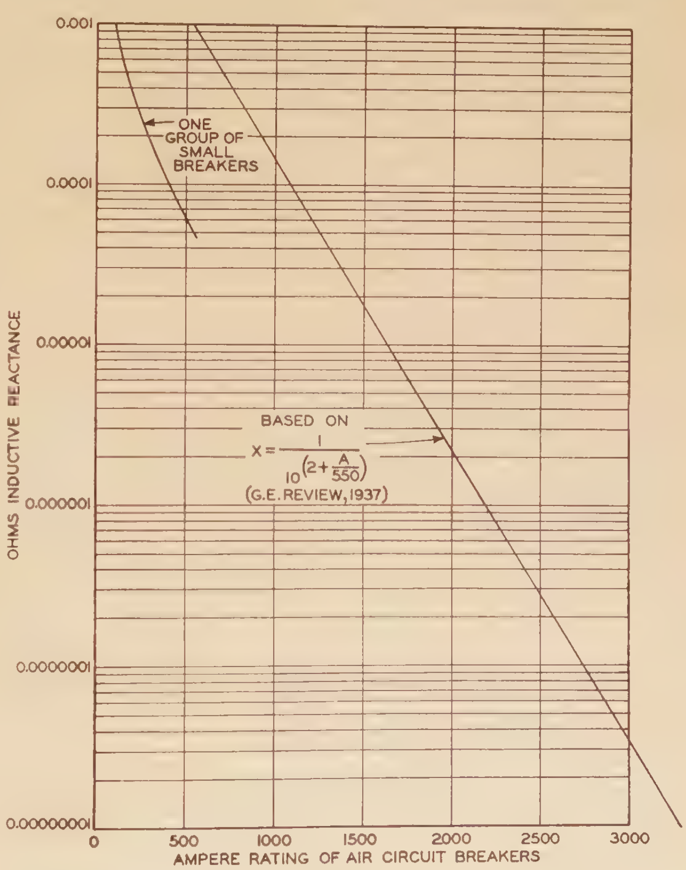


Figure 1. Inductive reactance of air circuit breakers

Presented informally at the conference on power distribution in industrial plants at the AIEE 1941 winter convention, Philadelphia, Pa., January 27–31.

RAYMOND C. R. SCHULZE is assistant engineer, Public Service Electric and Gas Company, Newark, N. J.

1. For all numbered references, see list at end of article.

using the impedance, where the impedance Z is equal to $\sqrt{R^2+X^2}$. In general, however, the values of X will be sufficiently greater than those of R that the reactance alone can be used without introducing too great an error. This statement is particularly true of transformers, generators, and reactors. It also applies to open-wire or open-bus construction for conductor sizes greater than 250,000 circular mils. For three-conductor cables, the resistance may be close to the reactance, but in general the reactances will be a little greater for conductor sizes in excess of 500,000 circular mils. Of course greater accuracy would be obtained by using the impedance, but generally the use of reactance is entirely satisfactory.

For the computation of reactance, the system can be divided into four general classes:

1. Air circuit breakers
2. Current transformers
3. Multiconductor cables
4. Open-wire circuits

The reactance of an air circuit breaker is almost entirely due to the trip coil itself. Values obtained for the same size of circuit breaker vary considerably, so it is difficult to give a general value. When it is impossible to obtain the correct value from the manufacturer, the following equation[1] may be used.

$$X_{acb}=\frac{1}{10^{\left(2+\frac{A}{550}\right)}} \qquad (2)$$

where A = ampere rating of the air circuit breaker. Values of X obtained from this equation are given in table I and in figure 1.

Table I. Inductive Reactance of Air Circuit Breakers

(60 Cycles)

Amperes	Values Given by Hanna[1]	Small Breakers
20		0.020
35		0.007
50		0.003
70		0.002
100		0.0009
150		0,0004
200		0.0003
250		0.0003
300		0.0002
350		0.0001
400	0.00185	0.0001
500		0.000050
550	0.001000	0.000050
600	0.000811	0.000050
700	0.000534	
800	0.000351	
900	0.000231	
1,000	0.000152	
1,100	0.000100	
1,200	0.000066	
1,300	0.000043	
1,400	0.000028	
1,500	0.000019	
1,650	0.000010	
1,800	0.0000042	
2,000	0.0000022	
2,200	0.0000010	
2,400	0.00000040	
2,600	0.00000019	
2,800	0.00000008	
3,000	0.000000035	

Current transformers of low current rating are especially important in a reactance diagram. The burden on the current transformer is also important, and should be estimated for each one in the system. The following equation[1] gives the impedance of a current transformer, and figures 2, 3, and 4 present this equation in graphical form. While current transformers of high current ratings do not affect fault currents particularly, those of low current ratings have considerable effect on fault currents at low voltages.

$$Z_{ct}=\frac{42.5+B}{I_p^2} \qquad (3)$$

where

B = secondary burden in volt-amperes

I_p = primary amperes, rating

Typical values of the volt-ampere burdens of various relays and meters are given in the "Relay Handbook Supplement".[2]

Multiconductor cables are handled in the usual way. Existing tables can be used. Table II gives some typical values.

Table II. Inductive Reactances of Three-Conductor Cables

Ohms Per Mile

Conductor Size		0000	00	1			
Circular Mils		500,000	400,000	300,000	211,600	133,225	83,521
Resistance ohms Per Mile		0.116	0.145	0.194	0.275	0.437	0.695
$^3/_{64}$ inch	X	0.127	0.129	0.132	0.135	0.139	0.145
	Z	0.172	0.195	0.235	0.308	0.460	0.711
$^4/_{64}$	X	0.131	0.134	0.136	0.140	0.146	0.152
	Z	0.175	0.197	0.237	0.309	0.461	0.713
$^6/_{64}$	X	0.136	0.138	0.141	0.146	0.153	0.162
	Z	0.178	0.201	0.240	0.313	0.464	0.715
$^8/_{64}$	X	0.146	0.149	0.154	0.161	0.171	0.182
	Z	0.186	0.208	0.246	0.320	0.471	0.697
$^{10}/_{64}$	X	0.153	0.157	0.162	0.170	0.182	0.195
	Z	0.192	0.230	0.254	0.323	0.474	0.721

From Westinghouse Electric and Manufacturing Company switchgear data book.

The designation "open-wire circuits" covers everything else in the distribution system. This refers to the usual three-phase line, or to buses or circuits made up of two or more conductors per phase, to bus work made up of flat bars, and is also used to include disconnecting switches and oil circuit breakers as parts of an open-wire circuit.

The reactance of the usual three-phase circuit made up of one conductor per phase is obtained in the usual manner. Any table of reactances of transmission lines may be used.

Since most tables do not cover the full range of large

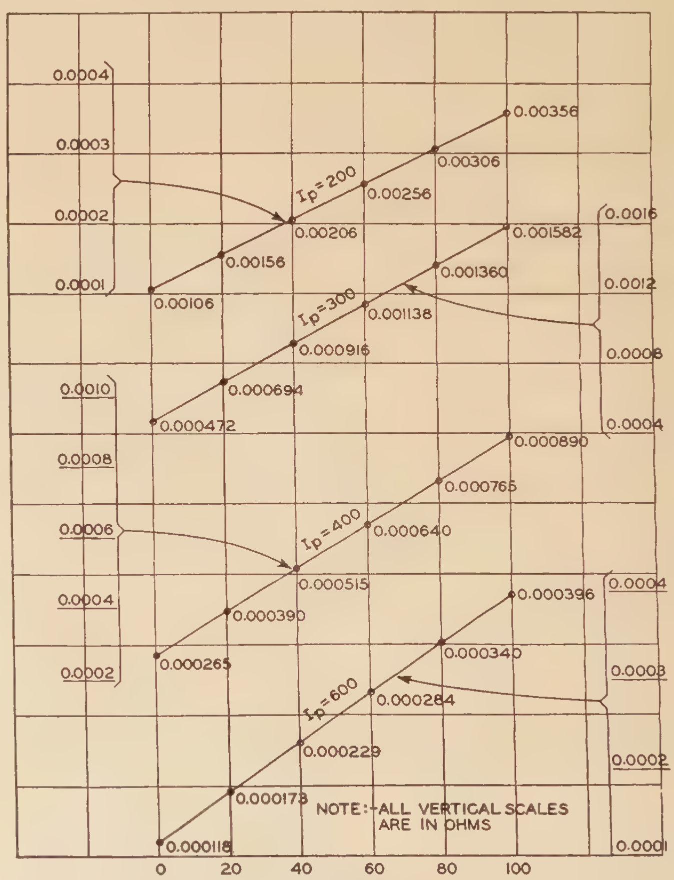


Figure 2. Impedances of current transformers with ratings of 200, 300, 400, and 600 amperes

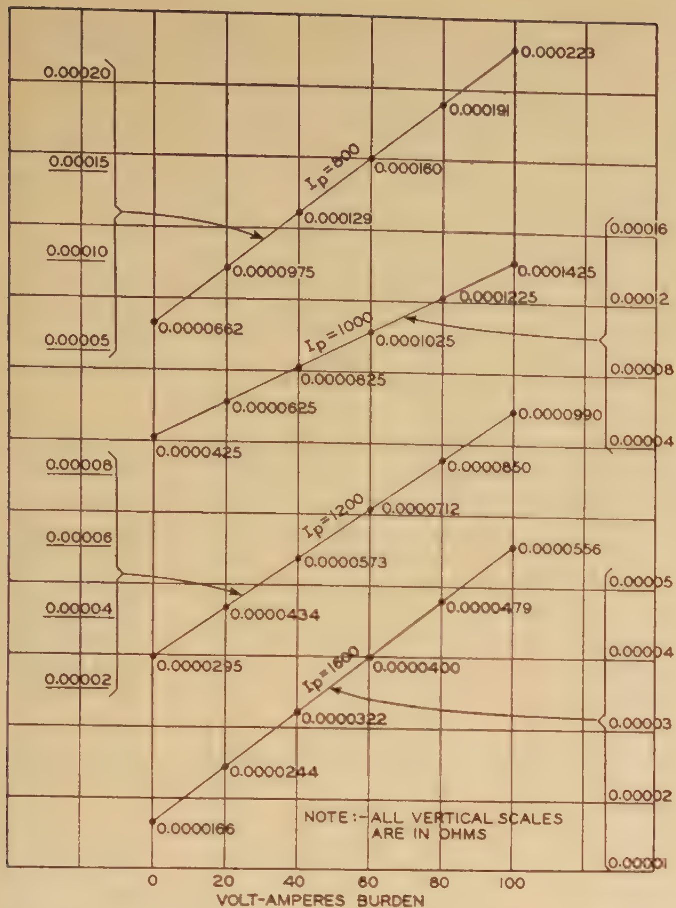


Figure 3. Impedances of current transformers with ratings of 800, 1,000, 1,200, and 1,600 amperes

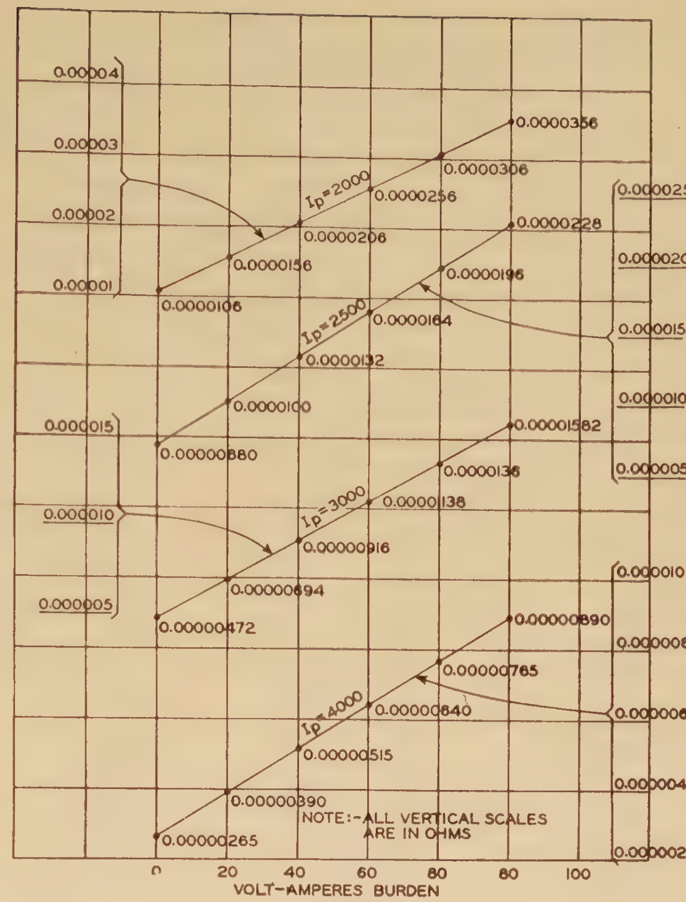


Figure 4. Impedances of current transformers with ratings of 2,000, 2,500, 3,000, and 4,000 amperes

wire sizes and small spacings encountered in low-voltage problems, the more complete and compact table III has been prepared. This table was prepared primarily for use on low-voltage short-circuit problems, where the conductor size may be in millions of circular mils. Any conductor can be replaced, in reactance equations, with an equivalent one, the equivalent conductor being a thin copper tube of radius $0.779R$. The reactance in ohms per 1,000 feet of one conductor of a circuit is

$$X = 0.0529 \log_{10} \frac{D}{R}$$

$$= 0.0529 \log D - 0.0529 \log R$$

These separate terms are given in columns 4 and 6 of table III. To find the reactance per phase, look up the proper values in columns 1 and 5, read the corresponding figures in columns 4 and 6, and subtract column 4 from column 6. The answer is ohms per 1,000 feet.

Example: Reactance of 250,000 circular-mil circuit, 36-inch spacing

$D = 36$ inches

column 6 = 10.0824 − 10
column 4 = 9.9653 − 10

0.1171 − 0

Nesbit[3] gives 0.1174. The new table may not be correct in the fourth place.

Column 3 of table III gives values of the equivalent mean radius R_{01} for use with the nomogram for equivalent mean radius of two-conductor group (figure 5).

If the spacings between the three conductors are all different, the spacing in column 5 of table III should be

$$D_{ab} = \sqrt[3]{D_{12} \times D_{23} \times D_{13}}$$

Where there is more than one conductor per phase, whatever the shape or size of these conductors, the first step is to convert all the conductors of any one phase into one equivalent conductor. This circuit of three equivalent conductors (one per phase) then is calculated as a conventional three-phase circuit.

One common case is the use of two round conductors per phase. To find the radius of the "equivalent conductor", use table III and figure 5. Column 3 of table III gives the equivalent mean radius of one actual conductor. On figure 5, place a straight edge between this value of equivalent mean radius of one actual conductor (left scale) and the distance between the two conductors of one phase (right scale); the left side of the center scale will give the equivalent mean radius of the equivalent conductor that replaces the two actual conductors. This process is made clearer by item 2 of the sample problem that follows.

Table IV gives values of ohms per phase for some conductor sizes and spacings used in past calculations.

Bus structures frequently are made up of flat copper bars, often with two or more bars per phase. All the bars in one phase group must be reduced to one equivalent conductor for that phase. The calculation of this equivalent conductor is slightly complicated. Table V gives

approximate values of the equivalent mean radius of this equivalent conductor, for various numbers of bars per phase, and various sizes of bars.

Oil circuit breakers and disconnecting switches are to

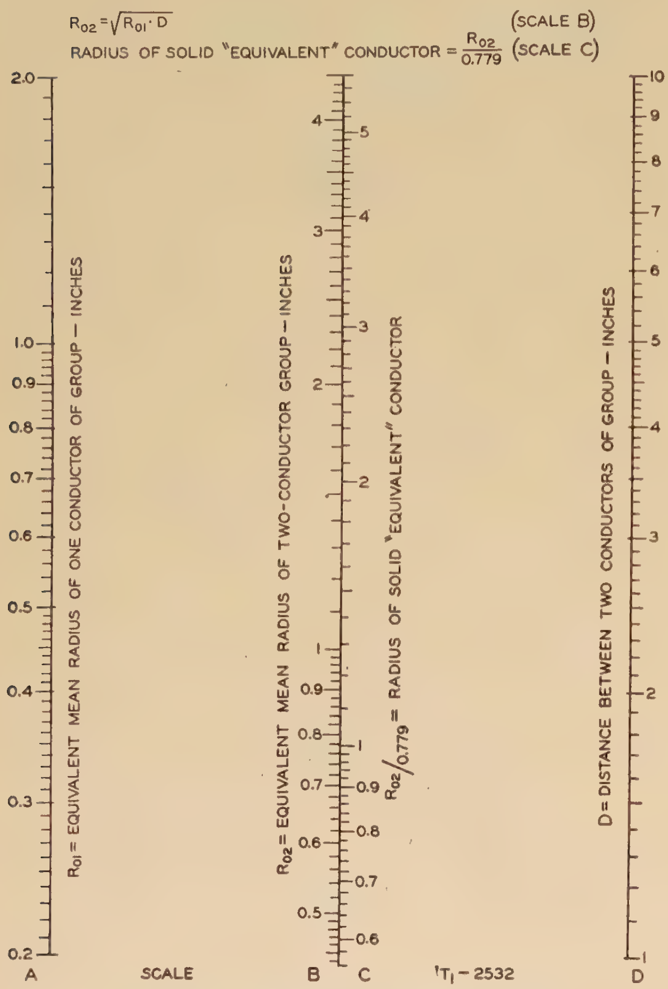


Figure 5. Equivalent mean radius of two-conductor group

Table III. Inductive Reactance Per Phase Wire in Ohms Per 1,000 Feet

All Dimensions in Inches

(1) Circular Mils	(1) Wire Size	(2) Diameter Stranded	(3) Equivalent Mean Radius	(4) 0.0529 × log R_0	(5) D_{ab}	(6) 0.0529 × log D_{ab}
	6	0.184	0.0668	9.9378–10	1.0	0.0000
	5	0.206	0.0748	.9404	1.5	0.0093
	4	0.232	0.0843	.9432	2	0.0159
	5	0.260	0.0944	.9458	3	0.0252
	2	0.292	0.1060	.9484	4	0.0319
	1	0.332	0.126	.9524	5	0.0370
	0	0.373	0.1413	.9553	6	0.0412
	00	0.418	0.158	.9576	7	0.0447
	000	0.470	0.178	.9603	8	0.0478
211,600	0000	0.528	0.200	.9630	9	0.0505
					10	0.0529
250,000		0.575	0.221	9.9653–10		
300,000		0.630	0.242	.9674	11	0.0551
350,000		0.681	0.262	.9692	12	0.0571
400,000		0.728	0.2795	.9707	13	0.0589
450,000		0.772	0.2965	.9721	14	0.0607
500,000		0.814	0.3125	.9733	15	0.0622
					16	0.0637
600,000		0.893	0.345	9.9755–10	17	0.0651
700,000		0.964	0.372	.9773	18	0.0664
800,000		1.031	0.398	.9788	19	0.0677
900,000		1.093	0.422	.9802	20	0.0688
1,000,000		1.152	0.445	.9814		
					21	0.0700
1,100,000		1.209	0.467	9.9825–10	22	0.0710
1,200,000		1.263	0.489	.9836	23	0.0721
1,300,000		1.315	0.509	.9845	24	0.0730
1,400,000		1.364	0.529	.9854	25	0.0740
1,500,000		1.412	0.546	.9861		
					26	0.0749
1,600,000		1.459	0.565	9.9869–10	28	0.0766
1,700,000		1.504	0.584	.9876	30	0.0782
1,800,000		1.548	0.600	.9883	32	0.0797
1,900,000		1.590	0.616	.9889	34	0.0810
2,000,000		1.631	0.633	.9895	36	0.0824
					38	0.0836
		1.7	0.661	9.9905–10	40	0.0848
		1.8	0.700	.9918		
		2.0	0.779	.9943	42	0.0859
		2.2	0.856	.9964	45	0.0875
		2.4	0.935	.9985	50	0.0899
		2.7	1.050	10.0011–10	55	0.0921
		3.0	1.169	.0038	60	0.0941
		3.5	1.361	.0071	65	0.0959
		4.0	1.558	.0102	70	0.0976
		5.0	1.948	.0153	80	0.1007
		6.0	2.338	.0195	90	0.1034
		8.0	3.116	.0261	100	0.1058
		10.0	3.895	.0312	120	0.1100

Table IV. Various Configurations and Reactances for Use in Station Service Bus Calculations

Configuration	Wire Size	No. of Phases	Drop Per Mile (Per Cent)*	Ohms Per Phase Per Mile	Ohms Per Phase Per 1,000 Feet
⊙—6″—⊙—6″—⊙ anything ⊙—6″—⊙—6″—⊙	1,500,000	See note†		0.318†	0.0602†
⊙—16″—⊙—16″—⊙	750,000	3		0.4798	0.09085
⊙—16″—⊙—16″—⊙	1,500,000	3		0.4378	0.0828
⊙—12″—⊙—12″—⊙ 9″ ⊙ ⊙ ⊙	1,500,000	3		0.2635	0.0499
⊙ ⊙ ⊙ ⊙ ⊙ ⊙ →|2¾″|←15″→|2¾″|←15″→|2¾″|←	1,500,000	3		0.3825	0.0725
⊙ ⊙ ⊙ ⊙ ⊙ ⊙ →|2¾″|←21″→|2¾″|←21″→|2¾″|←	1,500,000	3		0.4175	0.079
⊙ ⊙ ⊙ ⊙ ⊙ ⊙ →| 5″ |←9½″→| 5″ |←9½″→| 5″ |←	1,750,000	3		0.3178	0.0601
⊙ ⊙ ⊙ ⊙ ⊙ ⊙ →| 8″ |←12″→| 8″ |←12″→| 8″ |←	2,250,000	3		0.3205	0.0607
⊙—6″—⊙—6″—⊙—6″—⊙	1,000,000	2	26.3	9.55**	1.81**
⊙—6″—⊙—6″—⊙—6″—⊙	1,500,000	2	24.25	8.81**	1.67**

* Per cent drop at 4,800 kva, 2,400 volts.

† Note: Assumed to be two independent three-phase circuits; ohmic values are per circuit.

** Equivalent three-phase ohms at 13 kv.

be considered as parts of the three-phase circuits in which they are located.

In these calculations, no account is taken of the effect on the reactance of loops and angles in the open-wire circuits or bus structures.

The reactance of conductors in a nonmetallic conduit depends only on the conductor diameter and spacings. If the conductors are in an iron conduit, however, the reactances will be increased somewhat due to the presence of the iron. Test data on this effect have been presented by L. Brieger[4] of the Consolidated Edison Company of New York, Inc. These test data show that for the cases studied, the resistance would increase by a small percentage, but the reactance might increase by considerable percentages. Where the effect of the iron conduit must be known accurately, it is suggested that a measurement be made of the reactance of the particular feeder, or one like it.

Complete calculations for one example follow, illustrating the theory and the use of the reactance data presented.

Solution of Sample Problem

CALCULATION OF REACTANCES (FIGURE 6)

(1) Customer's Generator, 500 Kva, 20 Per Cent Reactance

This is assumed to be a relatively slow speed machine with salient poles; therefore it has a high reactance.

$X = E/I$

I at full load $= \dfrac{500{,}000}{3 \times 277} = \dfrac{500{,}000}{831} = 602$ amperes

E = volts drop across machine reactance

$= \dfrac{20}{100}(277) = 55.4$ volts

$X = \dfrac{55.4}{602} = 0.092$ ohm

(2) Customer's Generator, 500 Kva, 5 Per Cent Reactance

This is assumed to be a turbogenerator, high speed, with non-salient poles; therefore it has a low reactance.

By formula

$X = \dfrac{\% X 10(\text{kv}_{L-L})^2}{3\ \phi\ \text{kva}}$ ohms

$= \dfrac{5(10)(0.48)^2}{500} = \dfrac{5(10)0.23}{500}$

$= 0.023$ ohm

(3) Utility System

It is not always important to have the exact value of the reactance of the utility system, since it is usually a small part of the total value of parts 3, 4, 17, 5, 11, and 18 on the diagram (figures 6, 7, and 8); a large percentage error in the utility system reactance becomes a small percentage error in the total. If possible, the utility system reactance should be obtained from the utility system's engineers. If not obtainable, it should be estimated.

In this case, the utility system reactance is assumed to be 0.60 ohm at 4,150 volts; on the 480-volt base the system reactance is

$\left(\dfrac{480}{4{,}150}\right)^2 (0.60) = 0.0134(0.60) = 0.008$ ohm

It is necessary to convert all reactances to equivalent ohms at the same voltage base, as shown.

Table V. R_0 Values for Flat Copper Bars (Approximate)

Based on $R_0 = 0.2235\ (a+b)$

Size (Inches)	a+b	R_{01} (Inches)	R_0 for Several Bars in Parallel (Inches) 2	3	4	5	6
1/4 by 2	2.25	0.504	0.502	0.585	0.685	0.790	0.893
1/4 by 3	3.25	0.727	0.602	0.660	0.750	0.849	0.949
1/4 by 4	4.25	0.950	0.689	0.722	0.803	0.896	0.993
1/4 by 5	5.25	1.173	0.766	0.775	0.846	0.934	1.030
1/4 by 6	6.25	1.397	0.838	0.821	0.883	0.967	1.058

For 2 bars, $R_{02} = \sqrt[4]{R_{01} d^2} = 0.707\sqrt{R_{01}}$

For 3 bars, $R_{03} = 0.735\sqrt[3]{R_{01}}$

For 4 bars, $R_{04} = 0.813\sqrt[4]{R_{01}}$

For 5 bars, $R_{05} = 0.905\sqrt[5]{R_{01}}$

For 6 bars, $R_{06} = 1.005\sqrt[6]{R_{01}}$

NOTE 1. Spacing between center lines of bars = 0.50 inch.

NOTE 2. R_0 is a thin copper tube; when using tables (as in Nesbit[3]) divide these values by 0.779 to get the corresponding radius of a solid conductor.

(4) Transformer, 1,000 Kva (Three 333-Kva One-Phase Units), 3 Per Cent X, 4,150/480 Volts

By formula

$X = \dfrac{3(10)(0.480)^2}{1{,}000}$

$= \dfrac{3(10)0.23}{1{,}000}$

$= 0.0069$ ohm

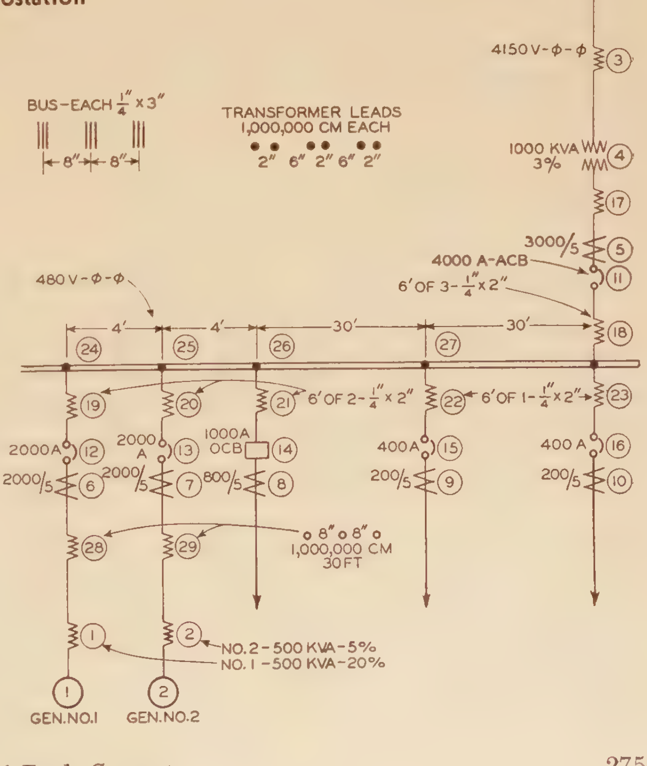
(5) Current Transformer, 3,000/5 Amperes

Burden:

	Volt-Amperes
Ammeter	2
Watt-hour meter	4
Overload relay	10
Directional overcurrent relay	14
Total	30

From figure 4, the impedance of this current transformer is 0.000008 ohm.

Figure 6. Diagram of sample customer substation



(6) (7) *Current Transformers, 2,000/5 Amperes*

Burden:

	Volt-Amperes
Ammeter	2
Wattmeter	2
Power-factor meter	4
Watt-hour meter	4
Overload relay	10
Directional overcurrent relay	14
Total	36

From figure 4, the impedance of each current transformer is 0.0000195 ohm; call it 0.000020 ohm.

(8) *Current Transformer, 800/5 Amperes*

Burden:

	Volt-Amperes
Ammeter	2
Watt-hour meter	4
Overload relay	10
Total	16

From figure 3, $Z=0.000091$ ohm.

(9) (10) *Current Transformers, 200/5 Amperes*

Burden:

	Volt-Amperes
Wattmeter	2
Ammeter	2
Total	4

From figure 2, $Z=0.0012$ ohm each.

(11) *Air Circuit Breaker, 4,000 Amperes*

The reactance of this air circuit breaker is about 0.0000000001 ohm, and can be neglected.

(12) (13) *Air Circuit Breakers, 2,000 Amperes*

From table I, the reactance of these breakers is probably less than 0.0000022 ohm each.

(14) *Oil Circuit Breaker, 1,000 Amperes*

Because this is an oil breaker, it will not be calculated separately, but instead will be considered as a part of the bus structure of item 21.

(15) (16) *Air Circuit Breakers, 400 Amperes*

From table I, the range of the reactance of these air breakers is probably between 0.00185 ohm and 0.00010 ohm. If exact data cannot be obtained from the manufacturer, it is probably better to take an average of the two limits given by the table, about 0.001000 ohm.

(17) *Leads From Transformer 480-Volt Bushings to Air Breaker*

1,000,000 circular mils each; length 12 feet

In table III, column 1, find 1,000,000 circular mils; for this size, in column 3, read equivalent mean radius of 0.445 inch. Refer to figure 5; set a straight edge at 0.445 on the *A* scale and at 2.0 on the *D* scale, and read on the *B* scale the value of 0.942 inch as the equivalent mean radius of each two-conductor group. The actual leads can now be represented in this way:

Each equivalent conductor has an equivalent mean radius of 0.942 inch

Equivalent triangular spacing of the three conductors is

$\sqrt[3]{8(8)(16)}=10.1$ inches

Refer again to table III. Values must be obtained from columns 4 and 6 for 0.942 inch in column 3 and 10.1 inches in column 5, respectively.

Column 3	Column 4
1.050	10.0011−10
.935	9.9985−10
0.115	0.0026

$0.942-0.935=0.007$

$\frac{0.007}{0.115}(0.0026)=0.00016=0.0002$

For 0.942, the value is $(9.9985-10)+0.0002=(9.9987-10)$

Column 5	Column 6
11	0.0551
10	0.0529
1.0	0.0022

$0.1/1.0(0.0022)=0.00022$

For 10.1 the value is $0.0529+0.0002=0.0531$

Value from column 6 10.0531−10
Value from column 4 9.9987−10

0.0544 ohm per phase per 1,000 feet

$\frac{12}{1,000}(0.0544)=0.000652$ ohm per phase for 12 feet of leads.

(18) *Leads From Air Breaker to Bus*

Each phase is made up of three 1/4- by 2-inch bars

In table V, the equivalent mean radius of one equivalent conductor which will replace three bars of 1/4- by 2-inch size (top row, fifth column from left) is 0.585 inch. It should be understood that this value of 0.585 is probably low, thus giving a value of reactance higher than actual, since skin and proximity effects were neglected.

The remaining procedure is the same as in the last two-thirds of the discussion under item 17.

$\sqrt[3]{8(8)(16)}=10.1$ inches

Column 3	Column 4
0.600	9.9883−10
0.584	9.9876−10
0.016	0.0007

$\frac{0.001}{0.160}(0.0007)=0.000004$

For 0.585 use 9.9876−10
From column 6 10.0531−10
From column 4 9.9876−10

0.0655 ohms per phase per 1,000 feet

For 6 feet

$X=\frac{6}{1,000}(0.0655)=0.00039$ ohm per phase

(19) (20) *Leads From Generator Air Breakers to Bus*

Each phase is made up of two 1/4- by 2-inch bars

From table V, read equivalent radius of 0.502 inch. Equivalent spacing is 10.1 inches.

0.509	9.9845−10
0.489	9.9836−10
0.020	0.0009

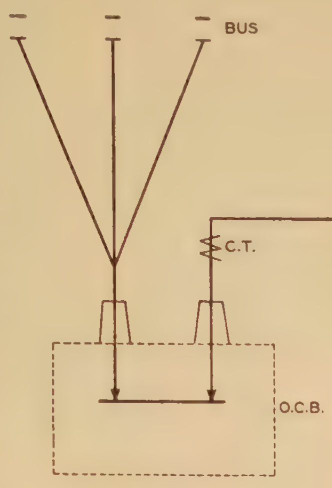
$(0.013/0.020)(0.0009)=0.00058$

For 0.502 use 9.9842 − 10
From column 6 10.0531 − 10
From column 4 9.9842 − 10

0.0689 ohms per phase per 1,000 feet

For 6 feet

$$X=\frac{6}{1,000}(0.0689)=0.000414 \text{ ohm.}$$



(21) Leads From Bus Through Oil Breaker to Current Transformer

In this case the reactance of the copper in the circuit-breaker bushings is considered as part of the "open-wire" construction from the bus to the current transformer. The total length from the bus to the current transformer is assumed to be 12 feet. Since the reactance per foot of length does not change much as the configuration changes, and a detailed calculation would take considerable time, it seems to be sufficiently accurate to consider the whole 12-foot length as being made up in the same way as the 6 feet of leads from the bus to the breaker.

These leads are two 1/4- by 2-inch bars (same arrangement as in items 19 and 20) so the reactance of item 21 becomes

$$\frac{12}{6}(0.000414)=0.00083 \text{ ohm}$$

(22) (23) Leads From Bus to Feeder Air Circuit Breakers

One 1/4-by 2-inch bar per phase

From table V, read equivalent radius of 0.504 inch (in column headed R_{01}). Equivalent spacing is 10.1 inches.

0.509	9.9845 − 10
0.489	9.9836 − 10
0.020	0.0009

(0.015/0.020) (0.0009) = 0.0007

For 0.504 use 9.9843 − 10

From column 6 10.0531 − 10
From column 4 9.9843 − 10

0.0688 ohms per phase per 1,000 feet

For 6 feet

$$X=\frac{6}{1,000}(0.0688)=0.000414 \text{ ohm}$$

(24) (25) Main Bus

Each phase is made up of three 1/4- by 3-inch bars

The procedure is the same as in items 18 to 23.
From table V, for size 1/4 by 3 inches, three bars in parallel, the equivalent radius is 0.660 inch. Equivalent spacing is 10.1 inches.
From table III,

Column 3	Column 4
0.661	9.9905 − 10
0.633	9.9895 − 10
0.028	0.0010

(0.027/0.028) (0.0010) = 0.00097 = 0.0010

For 0.660, use 9.9905 − 10
From column 6 10.0531 − 10
From column 4 9.9905 − 10

0.0626 ohms per phase per 1,000 feet

For 4 feet of bus length

$$X=\frac{4}{1,000}(0.0626)=0.00025 \text{ ohm}$$

(26) (27) Main Bus

Same arrangement as in items 24 and 25, so that ohms per phase per 1,000 feet are the same, but the length is different.
For 30 feet

$$X=\frac{30}{1,000}(0.0626)=0.00188 \text{ ohm}$$

(28) (29) Generator Leads

Each phase is one 1,000,000 circular-mil conductor. Distance, generator to current transformer, 30 feet

From table III, equivalent mean radius of one phase conductor is 0.445 inch. Equivalent spacing is 10.1 inches.

From column 6 10.0531 − 10
From column 4 9.9814 − 10

0.0717 ohms per phase per 1,000 feet

For 30 feet

$$X=\frac{30}{1,000}(0.0717)=0.002160 \text{ ohm}$$

These reactance figures now can be placed on the diagram as shown in figure 7. This figure also shows the assumed fault locations.

CALCULATIONS OF FAULTS (FIGURES 7 AND 8)

Fault at (A)

From utility system:

0.0080
0.0069
0.0149 ohm

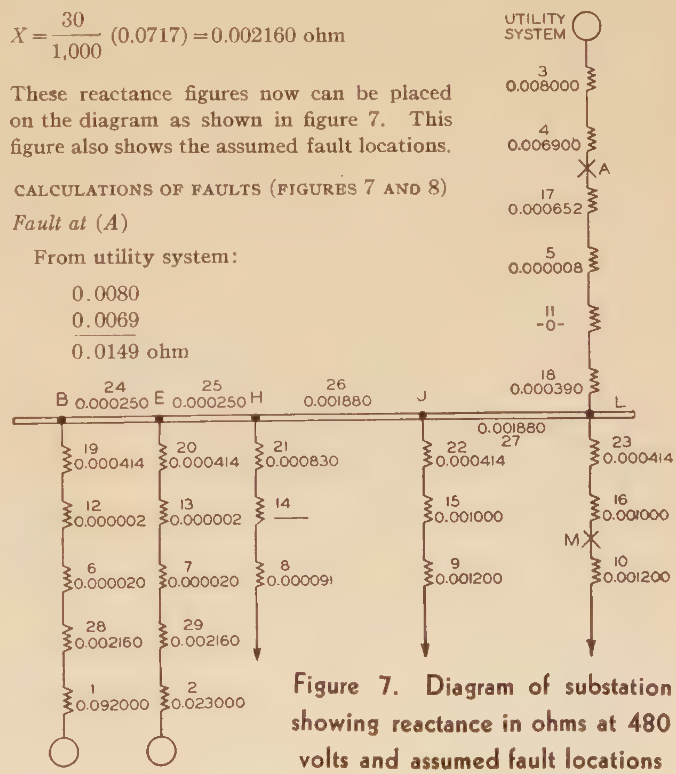


Figure 7. Diagram of substation showing reactance in ohms at 480 volts and assumed fault locations

1 to B	2 to E	1 to B to E
0.092000	0.023000	0.094596
0.002160	0.002160	0.000250
0.000020	0.000020	
0.000002	0.000002	0.094846
0.000414	0.000414	0.0948 ohm
0.094596	0.025596	
0.0946 ohm	0.0256 ohm	

$$\left.\begin{array}{ll}(1 \text{ to } B) + (B \text{ to } E) = & 0.0948\\ (2 \text{ to } E) & 0.0256\\ \hline & 0.1204\end{array}\right\}0.0202 \text{ ohm} \qquad \frac{\left.\begin{array}{c}a\\b\end{array}\right\}c}{a+b}$$

This value of 0.0202 ohm is obtained from equation

$$c=\frac{a+b}{ab}$$

where

c = combined value of two reactances in parallel

a and b = the separate parallel reactances

1 and 2 through E-J-H-L to A

$$\begin{array}{l}0.020200\\ \left.\begin{array}{l}0.000250\\0.001880\\0.001880\end{array}\right\}\ldots\ldots E \text{ to } L\\ \left.\begin{array}{l}0.000390\\0.000008\\0.000652\end{array}\right\}\ldots\ldots L \text{ to } A\\ \hline 0.025260\\ 0.0253 \text{ ohm from generator}\end{array}$$

Reactances of transformer and generators only = transformer + utility system . . . 0.0149 ohm

$$\text{generators}\ \left.\begin{array}{r}0.0920\\0.0230\\ \hline 0.1150\end{array}\right\}\ldots\ldots 0.0184 \text{ ohm}$$

$$\text{Short-circuit amperes} = \frac{\text{volts to neutral}}{\text{reactance}} = \frac{277}{X}$$

	Short-Circuit Amperes			
	Complete Reactances		Simplified Reactances*	
	Ohms	Amp	Ohms	Amp
From utility system	0.0149	18,600	0.0149	18,600
From generators	0.0253	11,000	0.0184	15,020
Total		29,600		33,620

* By "simplified reactances" is meant the use of transformer and generator reactances only; the effects of buses, air breakers, current transformers, leads, etc. is neglected.

Fault at (B)

Utility system to L to E:

$$\begin{array}{l}0.008000\\0.006900\\0.000652\\0.000008\\0\\0.000390\\0.001880\\0.001880\\0.000250\\ \hline \left.\begin{array}{ll}0.019960 = & 0.0200\\ 2 \text{ to } E & 0.0256\\ \text{Total} & 0.0456\end{array}\right\} \begin{array}{l}0.0112 \text{ ohm, combined from utility system}\\ \text{and generator number 2 to } E\end{array}\end{array}$$

0.00025 E to B

0.01145 ohm to B

Short-circuit amperes from generator number 1 . . . . 277/0.0946 = 2,940

Short-circuit amperes from generator number 2 and utility system . . . . . . 277/0.0115 = 24,100

Total 27,040

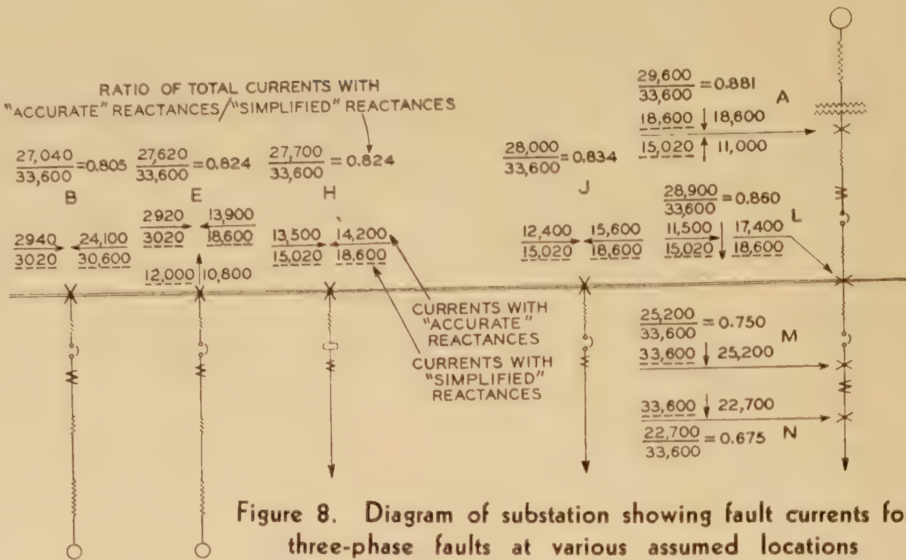


Figure 8. Diagram of substation showing fault currents for three-phase faults at various assumed locations

With simplified reactances

	Ohms	Amperes	
From generator number 1	0.0920	3,020	
From generator number 2	0.0230	12,000	30,600
From utility system	0.0149	18,600	
Total		33,620	

Fault at (E)

	Ohms	Amperes
1 to B to E (from calculations for A)	0.0948	2,920
2 to E	0.0256	10,800
Utility system to L to E		
Totaled under "Fault at (B)"	0.01996	13,900
		27,620
Simplified reactances:		
generator number 1	0.0920	3,020
generator number 2	0.0230	12,000
utility system	0.0149	18,600
Total		33,620

Fault at (H)

			Ohms	Amperes
1 to B to E	0.0948			
2 to E	0.0256	0.0202		
	0.1204			
E to H	0.00025			
	0.02045		0.02045	13,500
	0.01996			
	−0.00025			
	0.01970		0.0197	14,200
				27,700

By simplified reactances, as before, total = 33,620

Fault at (I)

		Ohms	Amperes
1 and 2 to E	0.02020		
	0.00025		
E to H to J	0.00188		
	0.02233	0.0223	12,400
Utility system to L to J	0.008000		
	0.006900		
	0.000652		
	0.000008		
	0.000390		
	0.015950		
	0.001880		
	0.017830	0.0178	15,600
			28,000

Fault at (L)

1 and 2 to E	0.02020		
	0.00025		
	0.00188		
	0.00188		
1 and 2 to L	0.02421	0.0242	11,500
Utility system to L	0.01595	0.01595	17,400
			28,900

Fault at (M)

Total reactance to L = 0.009600 ohm

$$\left.\begin{array}{r} 0.02410 \\ 0.01595 \\ \hline 0.04005 \end{array}\right\} 0.0096 \text{ ohm}$$

L to M	0.000414
	0.001000
Total reactance to M	0.011014 ohm

Total amperes at $M = 277/0.0110 = 25{,}200$

Fault at (N)

Total reactance to M	0.0110
M to N	0.0012
	0.0122

Total amperes at $N = 277/0.0122 = 22{,}700$

References

1. Calculation of Short-Circuit Currents in A-C Networks. W. M. Hanna, *General Electric Review*, 1937.

2. Relay Handbook Supplement, National Electric Light Association, 1931.

3. Electrical Characteristics of Transmission Circuits. William Nesbit.

4. Impedance of Three-Phase Secondary Mains in Nonmetallic and Iron Conduits. L. Brieger, Edison Electric Institute *Bulletin*, February 1938

Illumination Note

Flowing and Brilliant. California's well-known pride in her sons displays itself in a novel and spectacular manner by the illuminated cascade and fountain installed in the Joaquin Miller Park in Oakland and dedicated to California writers.

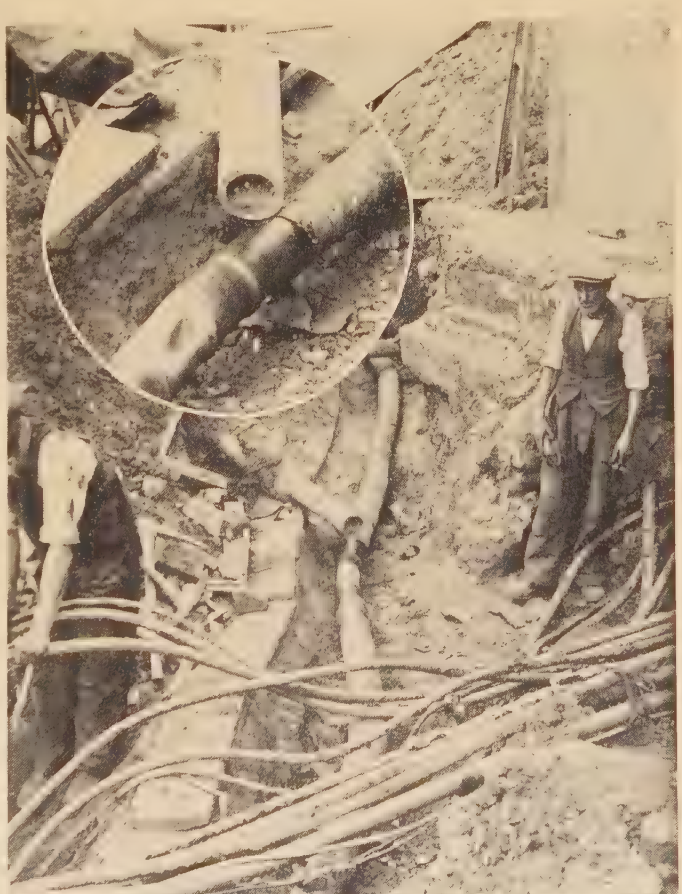
Jets, cascades, spray, and pools, supplied with about 1,000 gallons of water per minute, are illuminated in changing color by various combinations of floodlights and underwater lighting units. Control of the water flow and of the color and brilliance of the lights is electrical and automatic, with a normal cycle of about nine minutes, but of adjustable duration.

Contributed for the AIEE committee on production and application of light by L. A. Hawkins (A'03, M'13) executive engineer, research laboratory, General Electric Company, Schenectady, N. Y.

Compression Cable Withstands Bombing

WHAT happened to a Hochstadter compression-type cable in London, England, when an aerial bomb struck nearby may be seen from the accompanying illustration. Other than being forced slightly out of its original position and the enclosing pipe being dented in one place, the cable was not damaged and continued in service without interruption. The inset shows a closeup at the point where the cable enclosure was dented, the corrosion-protective covering having been removed over a short length. Adjacent cables were put out of commission, leaving the compression cable to carry the entire load for the areas it serves, and other underground structures were badly damaged. The bombing occurred near the point where the cable enters the substation.

This is said to be the first cable of its type; it was installed in London in 1932 and has been in continuous service since. It is a three-conductor 66-kv cable, and is enclosed in a five-inch steel pipe having a wall thickness of 0.167 inch, which is filled with gas at a pressure of 200 pounds per square inch.



Production—the Engineers' Defense Job

A Message From President Sorensen

THE PRESIDENT of the United States, according to the daily press, has declared there is need for still greater acceleration in the manufacture of machines and other defense requirements and that it may become necessary if that need is to be satisfied to withdraw from military service some of the engineers and others with specialized skills now engaged therein and assign them to work in factories making defense equipment.

President James Bryant Conant of Harvard University and others, who have recently been in England as special delegates from the United States, and have witnessed the actual conditions under which the English are waging their battle for democratic freedom, have observed the heartbreaking shortage of engineers, and have come to a full realization of the fact that mechanized war demands a very large number of engineers and skilled technicians for the design and manufacture of mechanical devices and the munitions used by them. The use of men with mechanical and engineering ability for any work other than the making of machinery seems at this time to be very unwise and even unpatriotic.

This issue of ELECTRICAL ENGINEERING contains an address, "Priorities in Men" by Doctor Harvey N. Davis, president of Stevens Institute of Technology, which was delivered May 2 at the AIEE Northeastern District Meeting in Rochester, N. Y. President Davis' address should be given careful study by manufacturing companies, selective service boards, college faculties, and all engineers.

As president of the AIEE I have been asked to comment regarding engineers and selective service. I am much interested in accepting the invitation, because I am wholeheartedly of the opinion that every engineer in training (which includes men in college and known to be ready for graduation at a certain time) or engaged in engineering service can for the time being best contribute to the production of defense paraphernalia for his country by continuing his established engineering program. Furthermore, I am of the opinion that the American Council on Education and those persons in Washington who are in charge of the national selective service system are in agreement with the thought that for the present "selective service" means that every engineer engaged in production engineering of any sort, as well as those in training for that production, should be kept at their work until conditions now prevailing have been changed by production having attained a pace which will, with safety to our defense program, permit the release of engineers from production jobs to what may be called operation occupations, one of which is military service as commonly understood.

Such a procedure does not indicate on the part of engineers any desire to avoid military service when that service is needed. Indeed the program of keeping engineers on production logically may be the best program for preparing these same men to render, when the time comes, the most effective kind of military service inherent in a mechanized military program. This is possible because men who have designed and made machines have a knowledge of how those machines should be operated that cannot be attained by any other experience.

The deferment of military service for engineers and their use at the vital defense business of manufacturing until the manufacturing program has reached a desired speed can be carried out without any change in the present selective service laws and without any onus being attached to the activities of engineers and technical men whose time for military service is deferred until the manufacturing bottleneck has been eliminated. The two essential features in such a program are the development of an understanding among our citizens of the critical need for engineers and technicians, and a complete mutual understanding and unanimous co-operation among selective service boards, manufacturing establishments, colleges, and the individuals involved.

Every factory today should be supporting the defense program by being engaged in making goods directly or indirectly applicable to the defense program. Those industries making goods directly applicable to the program should keep on the job every day every possible man whose leaving the job slows down or curtails the production of needed equipment for even as little as a few hours, because time is the essence of the program and every hour lost is gone forever and may prove very costly. Every engineer and skilled craftsman should be at one of these jobs. If he is not engaged in doing such a job, he should change his occupation to a defense productive job as soon as possible.

Every man who contemplates such a change, which includes every senior student, junior student, and graduate student in an engineering college who has a satisfactory record of achievement in his work and who will graduate as scheduled with his class, should be held to his program of preparation until it has been completed and should be allowed a reasonable time after graduation to obtain employment at some occupation where his training will be applicable to the defense program.

Every industry making defense equipment, therefore, whenever the enlistment for military service of one of their men doing good work in manufacturing comes up for consideration, should present to the selective service boards all the facts pertaining to the usefulness of the man in the manufacturing program.

Likewise, every engineering college, when a teacher or student is called by the selective service board, should supply the local selective service board with complete information regarding the man's status as teacher or student and argue fully as to his effectiveness and the need of his particular service in the program of training engineers and technical men.

In conjunction with the information presented by the industry or engineering college every individual engaged in defense production should, when called to report, file with his selective service board complete and accurate data regarding his work, including the time required to have a successor ready to carry on his work.

All this procedure is necessary and should not be considered as an attempt to avoid military service in any way. Quite the contrary, for in our mechanized military program of today such procedure is just a way of determining how every man may be kept where he can be of greatest service to the defense program. This idea naturally is not one readily conceived by many persons, because in all wars preceding the present one, battle strength has been determined to a much greater degree by the mere number of fighting soldiers available and the completeness of their training for marching and for hand-to-hand combat. In the present war the effectiveness of fighting forces is determined not by the gross number of men, but by the number and quality of machines available and the skill of a comparatively few men highly trained in the knowledge of how these machines are made and effectively operated. As has been said in this war the job at the traditional battle front seems to be for the few and the vital production job behind the line for the many. While this condition exists, we cannot afford to have any more men doing what some engineers in service are now doing: work routine such as issuing equipment to recruits.

In conclusion, therefore, while the need is for manufacture rather than for fighters, may I urge that industry, selective service boards, engineering-college faculties, and engineers in practice or in training, all co-operate to make production reach the desired goal, until such time as the need for technical ability in fighting forces begins to catch up with the demand for manufacturing ability. At which time, I am sure, every engineer will be more than willing to change from the job of manufacturing mechanisms of war to the job of operating these devices, and this they will do with a skill that would not be theirs had they not had the experience that is acquired in the factory.

1941 Summer Convention Program Completed

ALL arrangements have been completed for the AIEE summer convention to be held in Toronto, Canada, June 16–20, 1941, with headquarters in the Royal York Hotel. The business features of the convention will consist of ten technical sessions, five technical conferences, and one general session, in addition to the annual meeting, two sections of the conference of officers, delegates, and members, and the Branch counselors' conference. The summer convention committee, under the chairmanship of M. J. McHenry, has arranged an excellent series of social and recreational features beginning with an English tea party at 4:15 p.m. on Sunday, June 15. An account of these features, together with a schedule of events, was given in the May issue, pages 226–9. An additional inspection trip to view the highway lighting on the Queen Elizabeth Way has been added to the list already given.

H. COONLEY TO ADDRESS GENERAL SESSION

For this meeting of the AIEE in Canada, the program committee has selected as the theme of the general session the broad and all-important topic of co-operative effort in the support and further development of our system of free enterprise. This topic will be ably presented by Howard Coonley, chairman of the board of the Walworth Company and chairman of the advisory committee of the American Standards Association. AIEE members have occasion to remember well the stirring address "Total Security—a Challenge" delivered at the recent AIEE winter convention in Philadelphia and published in the March issue of ELECTRICAL ENGINEERING. Mr. Coonley's message at Toronto is expected to stress further the importance of every intelligent individual giving serious consideration to these vital topics of the day, and undoubtedly Mr. Coonley will inspire engineers to a more active and effective participation in, and will give many practical suggestions toward, the solution of the more significant problems facing democracy.

ROUTES TO TORONTO

For the summer convention, "all roads lead to Toronto," with excellent facilities for air, rail, or water travel, and excellent highways for automobile travel. From essentially all directions, travel to Toronto is easy. In most instances economical summer round-trip rates will be in force.

For those traveling from or through New York City or New England a special round-trip combination of steamer and train service is offered through the collaboration of the New York Central Railroad and the Canada Steamship Lines. The cost of this combined trip to Toronto, Montreal, and return, including Pullman accommodations on the train and meals and berth on the steamer, is quoted as $45.15 from New York City; $41.80 from Schenectady; and $49.30 from Boston. Canada Steamship Lines' steamers leave Toronto at 3 p.m. eastern standard time on Mondays, Wednesdays, and Saturdays for the trip across the length of Lake Ontario and through the Thousand Islands and the rapids of the St. Lawrence River, arriving at Montreal at 6:30 a.m.

Attention is called to the famous Saguenay River trip from Montreal, of three nights and two days duration. The all-expense cost, including meals and berth, is $38.00. Stopovers may be made at any point en route, such as Murray Bay or Tadoussac, or at Quebec.

The all-rail direct round trip from New York City to Toronto is quoted at $35.90 including Pullman lower berth but no meals. Trains providing through facilities leave New York at 9 a.m., 8:15 p.m., and 11:35 p.m., arriving at Toronto respectively at 8:20 p.m., 8 a.m., and 11:30 a.m.

Further information may be secured from J. P. Sweeney, New York Central Railroad, 466 Lexington Avenue, New York, N. Y.; or from J. J. Daly, Canada Steamship Lines, 535 Fifth Avenue, New York, N. Y.

ADVANCE REGISTRATION

Members who have received an advance registration card should fill in and return the card promptly, if they have not already done so. Hotel reservations should be made by writing directly to the Royal York Hotel, Toronto, Canada, or any other hotel preferred. For convenience, the rates of the Royal York and several other hotels were given in the May issue, page 229. The rate for a double room for two persons at the Royal York, incorrectly stated there as $6.00, is $7.00. For technical program see pages 282–3.

Howard Coonley to Address Summer Convention

Taking as his theme the need for strong and co-operative effort to insure the survival of the free-enterprise system and the democratic way of life, Howard Coonley, chairman of the board of the Walworth Company, New York, N. Y., will be the featured speaker at the general session, Thursday morning, June 19, of the AIEE 1941 summer convention at Toronto, Can.

HOWARD COONLEY

Mr. Coonley is chairman of the advisory committee of the American Standards Association, a past president of that organization, and past present, past chairman of the board, and currently chairman of the executive committee of the National Association of Manufacturers. A native (1876) of Chicago, Ill., he received his first business experience from 1900 to 1902 with the Chicago office of the Walter G. Baker Company. In 1902 he and his three brothers organized the Coonley Manufacturing Company, Cicero, Ill., to make enamel cooking utensils, of which he was vice-president 1902–08, and president 1908–30. He was also associated with his brothers in a pioneering enterprise in Texas in the early 1900s, which included development of cattle raising and farming and ultimately building several towns and a 40-mile railroad on a 100,000-acre tract.

In 1913 he became president of the Walworth Company, maker of valves, pipe fittings, and tools, and in 1936 became chairman of the board. For many years he has taken an active interest in improving the company's industrial relations and in promoting the safety, health, and welfare of its employees. He is a member of the American Society of Mechanical Engineers and of the Academy of Arts and Sciences.

Speakers Stress National Defense at North Eastern District Meeting

CONTINUING its traditional practice of giving prominent attention to the nontechnical as well as the technical phases of engineering enterprise, the AIEE North Eastern District featured a generous number of speakers on topics of general interest and importance during its recent Rochester meeting. The all-important all-pervading subject of national defense, in various aspects, furnished pretty much of a common theme for the various addresses.

The list of prominent speakers included Doctor Harvey N. Davis, president of Stevens Institute of Technology; Doctor Alan Valentine, president of the University of Rochester; Doctor R. H. Manson, vice-president and general manager, Stromberg-Carlson Telephone Manufacturing Company; Herman Russell, president, Rochester Gas and Electric Corporation; Doctor R. W. Sorensen, president AIEE; Everett S. Lee, vice-president AIEE, North Eastern District; and National Secretary H. H. Henline.

"Priorities in Men" was the topic to which Doctor Davis spoke in emphasizing what he termed as a defense necessity and patriotic duty of all parties concerned of conserving and allocating technically trained man power just as carefully and as intelligently as strategic inanimate materials are allocated under the priorities system. The

full text of Doctor Davis' address appears elsewhere in this issue. Doctor Sorensen, in remarks made upon various occasions, touched upon this as well as other matters of interest and significance to the Institute. In general, Doctor Sorensen's remarks are embraced by a written contribution which appears elsewhere in this issue, the third in a series of recent "Messages From the President" in which he has discussed topics relating to national defense.

In discussing "The Engineering Societies and National Defense," Mr. Henline briefly reviewed the scope and nature of the AIEE and of the national societies of civil, mining, and mechanical engineers, indicating some of the differences in principal interests and objectives. Touching upon co-operative activities, Mr. Henline mentioned briefly the national census of engineerng firms, the national roster of engineering and scientific personnel, the selection of co-ordinators for the Defense Contracts Service, the study of supply and demand of engineers, and the National Technological Civil Protection Committee. He pointed out that in addition to collaborating on matters of direct common interest such as the foregoing, each of the four societies are carrying on other activities best suited to the membership of the individual organizations, with appropriate collaboration, but naturally not all of the four doing the same thing. He reviewed typical AIEE efforts to co-operate in the matter of national defense, including the resolution adopted by the board of directors last June offering the services and facilities of the Institute to the Government, the series of six radio programs broadcast toward the end of this last winter, the decision to form an AIEE committee on national defense, the important local work undertaken by many Sections, and the many important technological contributions stimulated and facilitated through the work of the Institute's various committees.

Analysis of Registration at Rochester

Classification	Rochester Section	District 1*	Other Districts	Totals
Members	57	75	25	157
Enrolled Students	0	113	4	117
Men guests	27	25	8	60
Women guests	11	8	2	21
Totals	95	221	39	355

*Outside Rochester

North Eastern District Meeting Attendance 1931–1941

Date	Location	Attendance
1941—Apr. 30–May 2	Rochester, N. Y.	355
1939—May 3–5	Springfield, Mass.	439
1938—May 18–20	Lenox, Mass.	439
1937—May 5–7	Buffalo, N. Y.	371
1936—May 6–8	New Haven, Conn.	338
1934—May 16–18	Worcester, Mass.	337
1933—May 10–12	Schenectady, N. Y.	451
1932—May 4–7	Providence, R. I.	252
1931—Apr. 29–May 2	Rochester, N. Y.	370

Summer Convention

(Eastern Daylight

● **PAMPHLET** reproductions of authors' manuscripts of the numbered papers listed in this program may be obtained as noted in the following paragraphs.

● **ABSTRACTS** of papers appear on pages 290–3 of this issue and pages 230–1 of the May 1941 issue of Electrical Engineering.

● **PRICES** and instructions for securing advance copies of these papers accom-

Monday, June 16

9:00 a.m. Registration

9:30 a.m. Instruments and Measurements

41-106. Effect of Sapphire Crystal Orientation on the Wear of Watthour Meter Bearings. **J. H. Goss**, General Electric Company

41-108. An Improved Frequency Meter for Commercial Power Frequencies. **K. J. Knudsen**, Hickok Electrical Instrument Company

41-119. Power Circuit Instruments for the Higher Range of Audio-Frequencies. **L. J. Lunas** and **Paul MacGahan**, Westinghouse Electric and Manufacturing Company

41-125. Relative Accuracy of Three-Phase Metering Combinations. **C. T. Weller**, General Electric Company

41-112. The Shielding of Permanent Magnets From Transient Magnetic Fields. **G. J. Wey**, Westinghouse Electric and Manufacturing Company

9:30 a.m. Communication

41-113. Radio Broadcasting in Canada. **Augustin Frigon**, Canadian Broadcasting Corporation

41-129. The Measurement of Body Currents. **R. S. Schwab**, Massachusetts General Hospital

41-130-ACO.* Sound Recording for the Amateur. **A. L. Williams**, The Brush Development Company

41-111-ACO.* Phonograph Record Recording and Reproducing. **A. D. Burt**, RCA Manufacturing Company, Inc.

Wednesday, June 18

9:30 a.m. Basic Sciences and Electronics

41-103. A Short Method for Evaluating Determinants and Solving Systems of Linear Equations With Real or Complex Coefficients. **P. D. Crout**, Massachusetts Institute of Technology

41-105. Diode Rectifying Circuits With Capacitance Filters. **D. L. Waidelich**, University of Missouri

41-96. Measurement of Pre-breakdown Currents in Dielectrics With a Cathode-Ray Tube. **H. H. Race**, General Electric Company

41-107. Analytical Methods of Solving Discrete Nonlinear Problems in Electrical Engineering. **E. G. Keller**, Lockheed Aircraft Corporation

41-117. Current Rating With Life of Cold-Cathode Tubes. **G. H. Rockwood**, Bell Telephone Laboratories, Inc.

9:30 a.m. Insulation Testing

41-131. Impulse Strength as a Measure of Cable Quality. **L. I. Komives**, The Detroit Edison Company

41-118. The Basis for the Nondestructive Testing of Insulation. **R. F. Field**, General Radio Company

41-132. The A-C Dielectric-Loss and Power-Factor Method for Field Investigation of Electrical Insulation. **F. C. Doble**, Doble Engineering Company

41-120. Bushing Tests. **A. L. Brownlee** and **W. H. Wickham**, Commonwealth Edison Company

41-133. The Protection of Solid Insulation by Lightning Arresters. **D. D. MacCarthy** and **T. J. Carpenter**, General Electric Company

9:30 a.m. Switching Equipment

41-114. Mechanical Simplicity of Air-Blast Circuit Breakers. **H. W. Haberl**, Montreal Light, Heat, and Power, Consolidated, and **Otto Jensen**, I-T-E Circuit Breaker Company

41-121. System Short-Circuit Currents. **W. M. Hanna**, Consolidated Gas, Electric Light, and Power Company, **H. A. Travers** and **C. F. Wagner**, Westinghouse Electric and Manufacturing Company, and **C. A. Woodrow** and **W. F. Skeats**, General Electric Company

41-116. Power Circuit Breaker Ratings. **R. C. Van Sickle**, Westinghouse Electric and Manufacturing Company

41-128. Protection of Low-Voltage Circuits by Air Circuit Breakers in Cascade Arrangement. **A. E. Anderson** and **C. H. Black**, General Electric Company

41-134. Dielectric Strength of Oil for High-Potential Testing of Oil Circuit Breakers. **H. J. Lingal**, Westinghouse Electric and Manufacturing Company, **W. F. Skeats**, General Electric Company, and **H. D. Braley**, Consolidated Edison Company of New York, Inc.

2:00 p.m. Electrical Machinery

41-84. Methods of Determining Natural Frequencies in Coils and Windings. **L. V. Bewley**, Lehigh University, and **J. H. Hagenguth** and **F. R. Jackson, Jr.**, General Electric Company

41-110. Damping and Synchronizing Torque of the Double-Fed Asynchronous Machine. **M. M. Liwschitz**, Westinghouse Electric and Manufacturing Company

41-126. Transient Torques in Squirrel-Cage Induction Motors, With Special Reference to Plugging. **E. S. Gilfillan, Jr.**, and **Edward Kaplan**, Westinghouse Electric and Manufacturing Company

41-127. Excitation Circuits for Ignitron Rectifiers. **H. C. Myers** and **J. H. Cox**, Westinghouse Electric and Manufacturing Company

41-124. A New Transformer for Base Load Stations. **Philip Sporn**, American Gas and Electric Service Corporation, and **H. V. Putman**, Westinghouse Electric and Manufacturing Company

2:00 p.m. Relays and Bus Protection

41-99. Bus Protection Independent of Current Transformer Characteristics. **G. Steeb**, Buffalo, Niagara, and Eastern Power Corporation

41-135. New Current Transformers for Bus Differential Protection. **L. F. Kennedy** and **A. T. Sinks**, General Electric Company

Vice-President Lee spoke upon several occasions, introducing many a thought of inspiration and challenge. In his address of welcome, Mr. Lee emphasized the multiple capacity in which AIEE members were present for the Rochester meeting: as representatives of the 2,300 members of the North Eastern District with its 12 Sections and 18 Student Branches; as representatives of the AIEE's world membership of some 18,000; as representatives of "a million or more" engineers and scientists;

pany the abstracts. Mail orders are advisable, particularly from out-of-town members, as an adequate supply of each paper at the convention cannot be assured. Only numbered papers are available in pamphlet form.

● ALL PAPERS regularly approved by the technical program committee ultimately will be published in Transactions; many will appear also in Electrical Engineering.

41-109. A Simple Method for Determination of Ratio Error and Phase Angle in Current Transformers. **E. C. Wentz**, Westinghouse Electric and Manufacturing Company

41-122. D-C Machine Flashover and Bus Short-Circuit Protection. **T. B. Montgomery** and **J. F. Sellers**, Allis-Chalmers Manufacturing Company

41-102. Development in Lightning Protection of Stations. **E. R. Whitehead**, Duquesne Light Company

2:00 p.m. Conference on Industrial High-Frequency Heating by Means of Electronic Tubes

Heating by means of high-frequency currents has been an industrial process for a number of years. Alternating-current generators or some form of spark gap with an oscillating circuit have been used as converting devices. More recently two factors have served to make the use of electron tubes a more promising method than heretofore: first, the use of very high frequencies (megacycles) to give heating of material between capacitor plates due to dielectric losses; and second, a combination of higher power requirements than obtainable from a spark-gap type of converter in combination with a higher frequency than is practical from an alternator. It is hoped that those interested in the use of high-frequency heating, as well as those interested in the design of the equipment, will attend this conference.

Discussion leader: **W. C. White**, General Electric Company.

Thursday, June 19

10:00 a.m. General Session

President R. W. Sorensen, presiding

Address, "Co-operative Effort in Support of Our System of Free Enterprise." Howard Coonley, chairman of the board, Walworth Company, Inc.

2:00 p.m. Power Transmission

41-95. The 220,000-Volt System of the Hydro-Electric Power Commission of Ontario—II. **A. H. Frampton** and **E. M. Wood**, Hydro-Electric Power Commission of Ontario

41-94. Conductor Vibration—The Theory of Torsional Dampers. **J. W. Speight**, Hydro-Electric Power Commission of Ontario

41-97. Measurement and Control of Conductor Vibration. **G. B. Tebo**, The Hydro-Electric Power Commission of Ontario

41-115. Lightning to the Empire State Building—II. **K. B. McEachron**, General Electric Company

41-137. Field Investigations of Lightning. **C. F. Wagner, G. D. McCann**, and **Edward Beck**, Westinghouse Electric and Manufacturing Company

2:00 p.m. Industrial Power Applications

41-123. The Incandescent Lamp Situation From the Engineering Point of View. **P. S. Millar**, Electrical Testing Laboratories

41-136. A Distribution System for War-Time Plant Expansion. **J. L. McKeever**, Canadian General Electric Company, Ltd.

41-98. A New Mercury Rheostatic Element for Regulation and Control. **K. A. Oplinger**, Westinghouse Electric and Manufacturing Company

2:00 p.m. Conference on Education

Friday, June 20

9:30 a.m. Land Transportation

41-101. Electric Locomotive Application. **E.W. Brandenstein**** and **D. R. MacLeod**, General Electric Company

41-100. Glass Bulb Mercury-Arc Rectifiers for Traction Service. **C. E. Woolgar**, Northern Electric Company

41-104. Modern Motors Serve City Transit Systems. **W. J. Clardy** and **C. A. Atwell**, Westinghouse Electric and Manufacturing Company

9:30 a.m. Conference on Power Generation

This conference will continue the work of the January meeting on load swings, governing, system stability, and service continuity.

CP.† A Turbine Governor Performance Analyzer. **W. O. Osbon**, Westinghouse Electric and Manufacturing Company

CP.† Synthetic or Equivalent Load-Curves. **R. F. Hamilton**, Consulting Engineer

9:30 a.m. Conference on Protective Lighting

This conference will consider the protective lighting of factories against sabotage and espionage. The equipment for use, the distribution systems, and various sundry types of protective lighting will be discussed as well as black-out lighting as practiced in countries now at war from the point of view of possible future application.

2:00 p.m. Conference on Domestic and Commercial Applications

Brief summaries of work on the following topics in this field will be presented: motor-actuated appliances, heat-actuated appliances, interior wiring, and service requirements for industrial and commercial applications.

CP.† Controlling Domestic Washing Machines Automatically. **W. J. Russell**, Westinghouse Electric and Manufacturing Company

CP.† Domestic Oil Burner Controls. **W. H. DeLancey**, Gilbert and Barker Manufacturing Company

*ACO: Advance copies only available; not intended for publication in Transactions.

†CP: Conference paper; no advance copies are available; not intended for publication in Transactions.

**Deceased May 20, 1941.

as citizens with responsibilities paralleling their technical and professional enterprises and at least equally important.

Doctor Valentine, in a challenging address delivered before the entire assemblage at the banquet, urged engineers to endeavor to "help the people of the country to make the difficult discrimination between facts and opinions in the dangerous and difficult circumstances which so seriously threaten our security as a nation and our liberty as individuals." Doctor Valentine emphasized that a thoughtful and educated people, especially in an emergency such as the present, should discourage passion and name-calling; should encourage tolerance, especially with reference to minor or technical differences; should carefully distinguish between facts and opinions; should ever be on the alert to guard and preserve the Bill of Rights; should now "before the heat of battle" thoughtfully consider the kind of peace to be sought for and the desirable objectives and terms to be associated with it toward a constructive and durable result—citing a rapid and preconsidered peace is necessary if the hatreds and conflicting interests are not to be fanned anew by over-long negotiations.

Doctor Manson, in a necessarily limited way, indicated something of the significant contributions being made to national defense by the communications industry.

ATTENDANCE

The meeting of the North Eastern District in Rochester, N. Y., April 30–May 2, was the 15th such meeting to be held by the District and the second to be held in Rochester. The accompanying tables present an analysis of the attendance of this year's meeting and a comparison with recent part years.

STUDENT ACTIVITIES

Continuing the tradition of the North Eastern District, student activities were given a prominent place on the meeting program, including two student technical sessions and joint participation in many of the general activities and inspection trips. Of the 18 Student Branches in the North Eastern District, all but one were represented, many by relatively large groups. It was reported that in terms of round-trip traveled distances, the students present at Rochester represented about 80,000 man-miles of travel.

At a brief business session held immediately following a general luncheon, Professor Eric A. Walker, chairman of the North Eastern District committee on student activities was appointed to serve as the District's official counselor-delegate to the annual conference of officers, delegates, and members to be held as a part of the program for the forthcoming summer convention at Toronto.

The student technical sessions were arranged as follows:

Graduate Session

Peter Jaremko presiding.

The Beam Power Oscillator. **H. L. Kraus**, Yale University.

A Highly Sensitive D-C Amplifier Using A-C Power Exclusively. **S. E. Miller**, Massachusetts Institute of Technology.

Transients in Small Synchronous Machines. **Frank S. White Jr.**, Harvard University.

Impedance Matching of Directional Antenna Arrays. **C. W. Thulin**, Worcester Polytechnic Institute.

A New Tramsmitting Antenna for High-Definition Television. **Burton P. Brown Jr.**, University of Vermont.

Undergraduate Communications Session

H. L. Kraus presiding.

A High Impedance Voltage Indicator. **Leon E. Coff Jr.**, and **James F. Hasney**, Rhode Island State College.

The Ionosphere and Its Effect on Radio Waves. **S. K. Brown**, Cornell University.

Development of an Acoustical Resistance.

A. S. Chodakowski and **F. W. Ziegler,** Worcester Polytechnic Institute.

An Electronic Half-Cycle Counter. **B. E. Hand,** Massachusetts Institute of Technology.

Development of a High-Speed Watt-Second Recorder for Measurement of Transient Energies. **J. H. Arthur,** Rensselaer Polytechnic Institute.

Universal-Frequency Sweep Circuit. **W. A Knoop, Jr.,** Rensselaer Polytechnic Institute.

Undergraduate Power Session

J. Coolidge presiding

Some Problems in Secondary Grounding. **Arthur Eckels,** University of Connecticut.

Economics of Cable Testing. **Stephen J. O'Neil,** Northeastern University.

Effect of the Shape of Electrodes on the Breakdown Voltage of a Standard Insulaton. **Clayton H. Preble,** University of Maine.

Artificial Loading of Induction Machines by Unbalanced Voltages. **R. A. Muir** and **G. T. Douglass,** Worcester Polytechnic Institute.

Changes in Dielectric Constant of Alkali-Halide Crystals Under the Influence of Irradiation. **Milton Sanders,** Massachusetts Institute of Technology.

Doctor Scott Challenges Students. Doctor Charles F. Scott, past president of the Institute and a founder of AIEE Student Branch activities, and long a regular attendant at these gatherings, found himself unable to attend and sent the following challenging message to be read at the student luncheon:

"*To the AIEE Student Convention at Rochester:*

"As your District member of the National Committee on Student Branches I send you greetings.

"Nearly 40 years ago Branches were formed for bringing to the student the experience of older engineers and the professional attitude and understanding which may aid him in his future career. The reason why the Institute became interested in the development of men as well as technical matters was the rapid growth of the electrical industry and the increasing demand for competent engineers. The coming need of competent men is greater now than then.

"Just how can you make your Branch serve you in preparing you for your future career? I say how can *you* do this; not your counselor, or remote committees or Institute officers, but *you*, you students?

"The Branch is peculiarly your own affair. Curricula and schedules are prescribed; you follow orders. But the Branch is yours to do with what you want to do. It gives opportunity for collective action; action nowadays is by groups and organizations; your technical programs may have their most fruitful results—their by-products—in orderly composition, in effective presentation, in thinking on your feet, in keen discussion and in the handling of a meeting. Student conventions in the Southern District (where 17 institutions were represented last month) and in the Middle Eastern District (the January meeting in Pittsburgh) as well as in our own District, have convinced me of the high quality students are attaining. But nearly all papers are technical. Yet engineers must be more than technical. In the corridor of Dunham Laboratory at Yale are these words by an engineer, a soldier, an editor, and an industrial executive.

"Engineers reach the limit of their usefulness from defects of character rather than from want of technical attainments. Our greatest difficulty is to find courage, candor, imagination, large vision, and high ambition.

"Confirmatory is the result of a questionnaire responded to by many engineers which evaluates the qualities of the successful engineer as 25 per cent technical knowledge and skill and 75 per cent qualities listed by Colonel Prout. Now the 25 per cent is the concern of curriculum and professors' grades. The 75 per cent are personal qualities which it is your responsibility to develop. Are these matters simple and clear? What is their significance? If so much depends on nontechnical qualities why is this not a field for exploration by your Branch?

"Again, many of you are looking forward to belonging to the engineering profession. Just what does this imply? What is the difference between the engineering profession and technical employment? Should not your Branch become interested in the history, the present status, and the development of the engineering profession? How will professional organizations and codes of ethics and legal registration affect you?

"There are printed articles that may form a fruitful basis for your discussions. I want to urge your initiative and independent activity in exploring some of the nontechnical phases of engineering—those which may lead you to higher achievement and success.

"At the recent convention of the Southern District held at the University of Alabama it was voted that Branches should devote at least one meeting a year to professional topics and that papers for prizes be in two groups, one technical and one nontechnical."

DISTRICT EXECUTIVE COMMITTEE MEETING

The executive committee of the North Eastern District held a luncheon conference and business meeting at which various matters of business and plans for future activities were discussed. Action was taken establishing August 1 as the closing date for the submission of student papers for District prize awards for the preceding academic year.

The North Eastern District meeting and Student Branch convention for 1942 is scheduled to be held in Schenectady, N. Y.

This meeting was attended by the following delegates:

Everett S. Lee, vice-president, AIEE
R. G. Lorraine, secretary, North Eastern District
Eric A. Walker, chairman, District committee on student activities
Robert W. Adams, chairman, Boston Section
L. I. Albert, chairman, Tufts College Branch
H. A. Baines, chairman, Providence Section
E. A. Gruppe, chairman, Syracuse Section
M. G. Northrop, chairman, Ithaca Section
O. E. Sawyer, secretary, Providence Section
J. P. Wood, secertary, Ithaca Section
T. T. Woodson, secretary, Schenectady Section

Also in attendance at the meeting were President R. W. Sorensen, H. H. Henline, national secretary, New York, F. N. Tompkins, ex-chairman of Providence Section, Ex-Vice-President C. L. Dawes, Program Chairman E. B. Alexander of the Niagara Frontier Section, V. Siegfried, vice-chairman of the membership committee, G. W. Dunlap, delegate for Schenectady Section, W. K. Parks, secretary of Niagara Frontier Section, W. F. Cotter, chairman of the Rochester Section, G. W. Eighmy, chairman of the Niagara Frontier Section, and W. Irving Middleton, secretary of the Boston Section.

PRIZES AWARDED

Prizes awarded at Rochester to authors of technical papers included the following:

1. District prize for 1939–40 for initial paper—to H. R. Meahl, P. C. Michel, M. W. Sheldorf and T. M. Dickinson, for their paper "Measurements at Radio Frequencies," presented at the 1940 summer convention.
2. District prize for 1939–40 for best paper—to W. Mikelson and H. W. Bousman for their paper "Rapid-Recording A-C Bridge," presented at the 1940 summer convention.
3. District prize for 1939–40 for the best Student Branch paper—to T. F. C. Muchmore for his paper "A Study of Fluorescent Lamps" presented at the North Eastern District Student Convention, May 1940.
4. District honorable mention for Student Branch paper for 1939–40—to H. T. Marcy of Massachusetts Institute of Technology, Cambridge, for his paper "Measurement of Quadrature Synchronous Reactance Using Negative Excitation."

In addition to the foregoing more formal awards, the District maintained its tradition by making the following awards to enrolled students on the basis of the oral presentation of their papers at the Rochester meeting:

First prize, graduate session, to Burton P. Brown, Jr.

First prize, undergraduate communications session, to W. A. Knoop, Jr.

Second prize, undergraduate communications session, to A. W. Chodakowski and F. W. Ziegler

First prize, undergraduate power session, R. A. Muir and G. T. Douglass

Second prize, undergraduate power session, Stephen J. O'Neil

TECHNICAL SESSIONS

With the exception of the following two items subsequently added, the content of the technical program was in accordance with that published on page 177 of the recent April issue of Electrical Engineering:

DP. Secondary Networks for Supplying Power Plant Auxiliaries, H. G. Barnett, Westinghouse Electric and Manufacturing Company.

DP. Carrier-Current Relay Equipment and Its Other Uses, S. L. Goldsborough, Westinghouse Electric and Manufacturing Company.

With these additions the technical program at Rochester was made up of 10 regular technical-program papers destined for Transactions publication, 4 informal technical papers, and 4 technical addresses. In addition to these, of course, there were the 16 student technical papers and the various addresses on nontechnical topics. Average attendance at the technical sessions was about 75 or 80. The only parallel sessions were two of the student sessions.

A variety of prearranged inspection trips was available through the co-operation of the Rochester Telephone Corporation, the University of Rochester Medical School and the Physics and Optical Laboratories, the Rochester Products Division of the General Motors Corporation, the Rochester Gas and Electric Corporation, the Eastman Kodak Company, and other organizations.

In addition to the annual District banquet, the social and entertainment features offered included a smoker for the men and a paralleling dinner-bridge party for the women, various sight-seeing trips, and a general luncheon for students and others.

Section and Branch Activities—Annual Report for 1940–41

THE following constitutes the annual report on Institute Section and Branch activities for the fiscal year which ended April 30, 1941. Similar information for three preceding fiscal years appeared in ELECTRICAL ENGINEERING for June 1940, pages 250–3; June 1939, pages 268–71; June 1938, pages 263–6.

Present members of the Sections committee and the committee on Student Branches, which supervise the two important divisions of Institute activities covered by this report, are:

Sections—M. S. Coover, *chairman*, W. B. Morton, *vice-chairman and secretary*, C. A. Faust, O. W. Holden, E. T. Mahood, R. M. Pflazgraff, H. H. Race, I. Melville Stein, J. M. Thomson, W. H. Timbie, and *ex-officio* the chairmen of all Sections of the Institute.

Student Branches—H. W. Bibber, *chairman*, S. S. Attwood, W. C. DuVall, E. A. Loew, A. Naeter, C. W. Ricker, Charles F. Scott, E. M. Strong, R. G. Warner, and *ex-officio* all Student Branch counselors.

SECTION ACTIVITIES

Two new Sections were organized: Arizona, including the entire state, which had been within the territory of the Los Angeles Section, and South Bend, to which was assigned territory previously in the Chicago, Fort Wayne, and Michigan Sections. These made a total of 10 new Sections organized within the past four years.

On account of the extensive territories involved, the names of two Sections were changed: Charleston to West Virginia, and El Paso to New Mexico-West Texas.

President Sorensen visited a large number of Sections, and his address "Engineering Horizons, Limited", illustrated with many lantern slides, which was given in most cases, was received with unusual enthusiasm, as shown by the close attention of all audiences and a large number of complimentary comments received by the national secretary.

Two Sections reported no activity. Eight Sections held more than 15 meetings each, 9 held from 12 to 15, 38 held from 8 to 11, 10 held from 4 to 7, and 6 held from 1 to 3.

Doctor J. O. Perrine, assistant vice-president, American Telephone and Telegraph Company, addressed meetings of a considerable number of Sections with attendance as high as 3,230, and more than 1,000 at the majority of the meetings.

Fourteen Sections, which held a total of 132 Section meetings, also held 103 technical-group, committee, or other special meetings. The average attendance at 42 of these was at least 50 per cent of the average at the Section meetings, showing the continuing popularity of the more specialized meetings.

Many of the Sections held meetings devoted to national defense subjects. The Sections responded splendidly in supplying information needed in the Institute's co-operation with other societies in the census of engineering firms and the selection of ad-

Table I. Section Meetings Held During Last Three Fiscal Years

	Fiscal Year Ending April 30		
	1939	1940	1941
Number of Sections	67	70	72
Number of meetings held	635	701	703
Average number of meetings	9.5	10.0	9.8
Total attendance	85,692	91,949	92,554
Average attendance per meeting	135	131	132

Table II. Section Meetings Held During Year Ending April 30, 1941

Section	AIEE Members		Meetings During Year		Average Attendance as Per Cent of Membership, August 1940
	August 1939	August 1940	Number	Average Attendance	
Akron	75	85	7	74	87
Alabama	31	40	2	27	67
Arizona*			1	41	
Boston	414	415	8	168	40
Central Indiana	126	132	7	117	89
Chicago	733	769	6	198	26
Industrial group			3	114	
Power group			4	137	
Communication group			3	167	
Cincinnati	180	207	8	172	83
Cleveland	298	332	8	149	45
Technical group			6	82	
Columbus	95	92	11		
Connecticut	265	279	9	91	33
Denver	182	192	10	61	32
East Tennessee	118	132	10	46	35
Erie	65	57	10		
Florida	73	78	3	92	118
Fort Wayne	98	109	8	93	85
Georgia	104	109	6	90	83
Houston	139	141	10	234	166
Iowa	67	72	8	88	122
Ithaca	51	51	9		
Kansas City	125	148	9	166	112
Lehigh Valley	191	191	8		
Los Angeles	483	506	8	146	29
Louisville	56	61	10	36	59
Lynn	145	147	5	900	610
Inspection trips			4		
Technical lectures			5		
Local conventions			2		
Madison	65	67	8	87	130
Rock River Valley Subsection			6	40	
Mansfield	64	68	9	113	
Maryland	224	252	11	124	49
Memphis	61	72	10	45	63
Mexico	56	56			
Michigan	358	376	8	179	48
Round-table discussions			1		
Milwaukee	270	280	8	144	51
ESM meetings			1	200	
Minnesota	89	107	11	97	91
Power group			1	30	
Montana	39	36	6	127	128
Muscle Shoals	46	33	9	49	148
Nebraska	56	48	5	48	100
New Mexico-West Texas		47	9	37	79
New Orleans	97	123	8	58	48
New York	3,355	3,346	5	460	14
Communication group			3	123	
Basic Science group			6	137	
Power group			12	209	
Illumination group			2	173	
Transportation group			3	342	
Niagara Frontier	201	197	9	65	33
North Carolina	85	91	2	104	114
North Texas	140	170	10	511	300
Oklahoma City	120	117	10	299	256
Philadelphia	610	650	9	200	31
Pittsburgh	517	564	10	221	39
Technical meetings			2	126	
Pittsfield	178	192	8	778	405
Technical meetings			5		
Colloquium meetings			4	42	
Popular meetings for high-school students			5	800	
Portland	151	176	9	69	39
Communication committee			4	41	
Transmission and distribution committee			4	69	
Providence	91	99	8	64	65
Rochester	95	103	12	89	86
St. Louis	268	273	9	393	144
San Antonio	43	45	7	44	98
San Diego	30	36	9	29	81
San Francisco	486	507	12	129	25
Technical meetings			5	87	
Saskatchewan	21	15	6	8	53
Schenectady	403	434	10	113	26
Technical discussion meetings			3	173	
Seattle	153	164	10	82	50
Technical group			2	55	
Electronics group			1	80	
Sharon	86	105	9	133	127
South Bend**			3		
South Carolina		37	3	36	97
Spokane	62	81	12	39	48
Springfield	60	57	9	91	160
Syracuse	71	75	6	130	173
Toledo	78	71	11	101	142
Toronto	338	342	14	211	62
Tulsa	107	94	8	121	129
Urbana	77	76	6	175	230
Utah	76	76	12	52	68
Idaho technical committee			6	26	
Vancouver	107	97	11	42	43
Virginia	94	111			
Washington	332	370	14	138	37
Junior technical sessions			19	35	
West Virginia		48	5	37	77
Wichita	46	52	10	150	289
Worcester	58	63	8	58	92
Total.....72	14,078	14,844			

Total number of meetings.............. 703
Total attendance.......................92,554

* Organized March 22, 1941.

** Organized February 26, 1941.

Table III. Branch Meetings Held During Year Ending April 30, 1941

Branch	Meetings During Year: Number	Meetings During Year: Average Attendance	Approximate Number of Talks by Students
Akron, University of	4	26	1
Alabama Polytechnic Institute	8	34	1
Alabama, University of	11	24	4
Alberta, University of	10	23	14
Arizona, University of	22	9	16
Arkansas, University of	15	22	16
British Columbia, University of	6	25	10
Brooklyn, Polytechnic Institute of			
Day division	15	64	2
Evening division	9	28	1
Brown University	2	48	
Bucknell University	4	12	
California Institute of Technology	15		3
California, University of	27	34	7
Carnegie Institute of Technology	29	50	20
Case School of Applied Science	4	27	2
Catholic University of America	2	27	
Cincinnati, University of	11	91	8
Clarkson College of Technology	3	14	
Clemson Agricultural College	13	38	18
Colorado State College	6	20	4
Colorado, University of	9	172	1
Columbia University	5	22	
Connecticut, University of*	3	68	
Cooper Union			
Day division	4	24	
Evening division	13	28	5
Cornell University	5	27	
Denver, University of	6	35	
Detroit, University of	7	72	1
Drexel Institute of Technology	10	16	3
Duke University	9	23	
Florida, University of	2	28	2
George Washington University	5	63	3
Georgia School of Technology	5	61	
Harvard University	6	28	5
Idaho, University of	11	25	2
Illinois Institute of Technology	14	46	4
Illinois, University of	9	168	
Iowa State College	10	114	
Iowa, University of	27	42	28
Johns Hopkins University	15	26	16
Kansas State College	12	178	3
Kansas, University of	8	38	2
Kentucky, University of	23	62	2
Lafayette College			
Lehigh University	6	48	1
Louisiana State University	8	23	2
Louisville, University of	2	19	1
Maine, University of	10	16	4
Manhattan College†	1		
Marquette University	8	25	2
Maryland, University of	7	24	7
Massachusetts Institute of Technology	3	42	
Michigan College of Mining and Technology	8	31	2
Michigan State College	12	32	
Michigan, University of	6	44	
Milwaukee School of Engineering	3	57	1
Minnesota, University of	11		3
Mississippi State College	5	32	1
Missouri School of Mines and Metallurgy	9	33	7
Missouri, University of	8	35	3
Montana State College	28	29	89
Nebraska, University of	18	50	12
Nevada, University of	12	23	3
Newark College of Engineering	10	40	5
New Hampshire, University of	6	22	1
New Mexico State College	13	15	12
New Mexico, University of	12	13	7
New York, College of the City of			
Day division	22	48	1
Evening division			
New York University			
Day division	4	26	
Evening division	9	16	
North Carolina State College	14	46	3
North Dakota Agricultural College	6	12	4
North Dakota, University of	12	16	3
Northeastern University	12	69	6
Northwestern University	7	37	1
Norwich University**	1	33	
Notre Dame, University of	8	33	2
Ohio Northern University	8	42	1
Ohio State University	13	36	8
Ohio University	7	15	1
Oklahoma A.&M. College	12	287	2
Oklahoma, University of	9	42	2
Oregon State College	12	59	8
Pennsylvania State College	6	185	
Pennsylvania, University of	4	70	6
Pittsburgh, University of	24	89	23
Porto Rico, University of	1	43	
Pratt Institute	13	47	4
Princeton University	1	17	
Purdue University	12	103	
Rensselaer Polytechnic Institute	6	46	
Rhode Island State College	11	24	
Rice Institute	13	36	4
Rose Polytechnic Institute	6	23	3
Rutgers University	5	22	3
Santa Clara, University of	11	18	8
South Carolina, University of	3	23	
South Dakota State College	17	17	8
South Dakota State School of Mines	7	16	
Southern California, University of	14	28	10
Southern Methodist University			
Stanford University	14	31	
Stevens Institute of Technology			
Swarthmore College	2	17	
Syracuse University	7	16	7
Tennessee, University of	5	24	
Texas A. and M. College	11	48	5
Texas Technological College	10	29	1
Texas, University of	12	63	
Tufts College	5	32	
Tulane University	10	26	6
Union College	5	53	
Utah, University of	15	34	10
Vermont, University of	10	19	5
Villanova College	5	12	3
Virginia Military Institute	3	44	6
Virginia Polytechnic Institute	19	51	9
Virginia, University of			
Washington, State College of	15	52	4
Washington, University of	10	55	3
Washington University	13	26	
West Virginia University	14	36	62
Wisconsin, University of	5	60	1
Worcester Polytechnic Institute	2	50	6
Wyoming, University of	9	45	1
Yale University	7	30	1
Total......123 Branches			608
Total number of meetings	1,163		
Total attendance		52,285	

* Authorized by board of directors, January 30, 1941.

† Authorized by board of directors, January 30, 1941.

** Authorized by board of directors, May 24, 1940.

visors to district co-ordinators in the defense contract service.

A comprehensive summary of Section activities during the year 1939–40, based on replies to questionnaires prepared by the Sections committee, was published in the October issue of ELECTRICAL ENGINEERING, pages 425–8. This includes a table showing in detail the many types of activities in which 54 Sections participate.

Table IV. Branch Meetings Held During Last Three Fiscal Years

	Fiscal Year Ending April 30: 1939	1940	1941
Number of Branches	120	121	123
Number of meetings held	1,190	1,346	1,163
Average number of meetings	9.9	11.1	9.5
Total attendance	53,380	64,972	52,285
Average attendance per meeting	44.8	48.3	45.0
Number of student talks	725	767	608

Table V. Conferences on Student Activities

District	Location	Date
1	Rensselaer Polytechnic Institute, Troy, N. Y.	5/3–4/40
8 and 9, University of British Columbia	Los Angeles, Calif. (Pacific Coast convention)	8/27–30/40
2	Cincinnati, Ohio (Middle Eastern District meeting)	10/9–11/40
4	University of Alabama, University, Ala.	4/3–5/41
6	University of Denver, Denver, Colorado	4/18–19/41
7	University of Missouri, Columbia, Mo.	4/28–29/41
1	Rochester, N. Y. (North Eastern District meeting)	4/30–5/2/41

Table VI. Student Conventions

Sponsor (District, Section, or Branch)	Location	Date	Number of Student Papers
1	Rensselaer Polytechnic Institute, Troy, N. Y.	5/3–4/40	21
8 and 9, University of British Columbia	Los Angeles, Calif. (Pacific Coast convention)	8/27–30/40	10
4	University of Alabama, University, Ala.	4/3–5/41	6
6	University of Denver, Denver, Colo.	4/16–18/41	9
3 and New York Section	Rutgers University, New Brunswick, N. J.	4/24/41	8
7	University of Missouri, Columbia, Mo.	4/28–29/41	
2	University of Pennsylvania, Philadelphia, Pa.	4/28/41	6
1	Rochester, N. Y. (North Eastern District meeting)	4/30–5/2/41	16

In an effort to measure the value to the Sections of the surveys of Section activities made during the past few years, the committee distributed a questionnaire in April. A report based on the responses will be discussed at the conference of officers, delegates, and members at the 1941 summer convention in Toronto.

In September 1940, only 93 members of the Institute within the United States were outside of Section territories. Section membership records as of August 1, 1940, gave the total membership of the Sections in the United States as 14,338.

The Sections committee has continued its study of unassigned territory with the object of recommending further revisions when desirable. The other activities of the Sections committee have included the adoption of a trial plan for publishing information on Section meetings in ELECTRICAL ENGINEERING, plans to develop greater interest among the Sections in vocational guidance, and efforts to develop more effective distribution of the pamphlets "The Electrical Engineer" and "Engineering—A Career, a Culture".

Table I contains detailed information regarding membership and meetings of the individual Sections, table II shows a comparison over the past three years, and table VII shows the extent of student participation in Section and joint Section and Branch meetings.

STUDENT ACTIVITIES

New Student Branches were organized at the University of Connecticut, Storrs; Norwich University, Northfield, Vt.; and Manhattan College, New York, N. Y. Armour Institute of Technology and Lewis Institute, both in Chicago, were combined under the name Illinois Institute of Technology, and therefore the two Student Branches were combined into the Illinois Institute of Technology Branch. The total number of Branches at the end of the year was 123.

The students have continued their keen interest in presenting papers at the Pacific Coast convention and District meetings, presenting 11 papers in 2 sessions at the Pacific Coast convention, and 16 papers in 3 sessions at the North Eastern District meeting, in Rochester. As shown in table VII, 30 Branches co-operated with 20 Sections in holding 21 Section or joint Section and Branch meetings in which students presented 67 papers.

Only one Branch failed to report any activity during the year. Thirteen Branches held more than 15 meetings each, 27 held from 12 to 15, 30 held from 8 to 11, 36 held from 4 to 7, and 16 held from 1 to 3.

The total number of Branch meetings held during the year was 1,163, and 608 student talks were presented, both numbers being considerably lower than those for the preceding year. Although 9 Branches had 15 or more student talks, and 27 had from 5 to 14, 52 had only from 1 to 4, and 35 had none.

Of 1,641 Enrolled Students whose terms were expected to expire on April 30, 1941, 887 or about 54 per cent applied for admission as Associates. The records for the preceding year were 1,624, 911, and about 56 per cent. Tables III, IV, V, VI, and VII contain detailed information on Branch meetings, District conferences, student conventions, and student participation in Section and joint Section and Branch meetings.

Table VII. Section or Joint Section and Branch Meetings With Active Student Participation

Sections	Branches	Date	Student Talks	Attendance
Cincinnati	University of Cincinnati	5/9/40	4	195
New Orleans	Louisiana State University Tulane University	5/13/40	2	70
Worcester	Worcester Polytechnic Institute	5/14/40	5	65
Oklahoma City	University of Oklahoma	5/15/40	1	127
St. Louis	Missouri School of Mines and Metallurgy University of Missouri Washington University	5/17/40	6	110
Portland	Oregon State College	5/18/40	3	99
Tulsa	University of Arkansas Oklahoma A. and M. College	5/18/40	4	70
Utah	University of Utah	5/20/40	3	44
Florida	University of Florida	12/27/40	2	56
Pittsburgh	Carnegie Institute of Tech. Pennsylvania State College University of Pittsburgh West Virginia University	1/14/41	4	292
Akron	University of Akron	1/14/41	1	68
Toronto	University of Toronto	1/20/41	4	82
Vancouver	University of British Columbia	3/3/41	3	51
Los Angeles	California Institute of Tech. University of Southern Calif.	4/8/41	5	120
Houston	Texas A. and M. College Rice Institute	4/9/41	5	68
Seattle	University of Washington	4/14/41	2	56
Cleveland	Case School of Applied Science	4/17/41	3	82
New Orleans	Tulane University	4/18/41	2	39
Minnesota	University of Minnesota	4/22/41	4	60
Louisville	University of Louisville	4/25/41	1	40
San Francisco	University of Santa Clara Stanford University	4/25/41	3	80
Totals—20 Sections, 30 Branches, 21 Meetings			67	1,874

National • • • •

Committee Announces 1940 AIEE National Prize Awards

National prize awards for papers presented during 1940 have been announced by the AIEE committee on the award of Institute prizes. The committee had the benefit of recommendations on all except Branch papers from the chairmen of technical committees, and selection was made from all eligible papers presented in 1940. No award is being made for best paper in public relations and education as no eligible papers in this category were presented during 1940. The prizes will be awarded at the annual meeting of the Institute, June 17, 1941, during the coming summer convention at Toronto, Canada.

The announcement was made by P. L. Alger, acting chairman of the committee, for J. W. Barker, chairman. Other members of the committee are W. F. Davidson and D. M. Simmons.

Papers receiving awards in the several classifications, and their authors, are:

Best Paper in Engineering Practice: Prize awarded jointly to D. R. Shoults (A'35), M. A. Edwards (M'40), and F. E. Crever (A'37), of the General Electric Company, for their paper on "Industrial Applications of Amplidyne Generators", presented at the winter convention, January 22–26, 1940, and published in the 1940 TRANSACTIONS, pages 944–9; and to J. W. Milnor (A'13, F'30) of the Western Union Telegraph Company, for his paper on "Control of Inductive Interference Telegraph Systems", presented at the 1940 winter convention and published in the 1940 TRANSACTIONS (August section), pages 469–74. Honorable mention was made of the paper "The Development of the Civil Aeronautics Authority Instrument Landing System at Indianapolis", by W. E. Jackson, Civil Aeronautics Authority; A. Alford (A'39) and P. F. Byrne, International Telephone Development Company; and H. B. Fischer, Bell Telephone Laboratories, Inc., which was presented at the 1940 winter convention and published in the 1940 TRANSACTIONS, pages 849–58.

Best Paper in Theory and Research: Prize awarded to E. C. Starr (M'29), Oregon State College, for his two papers "High-Voltage D-C Point Discharges" and "Aircraft Precipitation-Static Radio Interference", presented at the summer convention, June 24–28, 1940, and published in the 1941 TRANSACTIONS, pages 356–62 and 363–70. Honorable mention was made of the paper "Theory of Hysteresis Motor Torque" by B. R. Teare, Jr. (A'29, M'36), Carnegie Institute of Technology, which was presented at the 1940 winter convention and published in the 1940 Transactions, pages 907–12.

Initial Paper: Prize awarded to V. E. Legg (M'37), and J. F. Given (A'28), Bell Telephone Laboratories, Inc., for their paper "Compressed Powdered Molybdenum Permalloy for High-Quality Inductance Coils", presented at the winter convention and published in the 1940 TRANSACTIONS, pages 865–72.

Branch Paper: Prize was awarded to W. H. Huggins (Enrolled Student) Oregon State College, for his paper "A Stabilized Neon-Tube Direct-Coupled Amplifier", presented at a joint meeting of the Portland Section and the Oregon State College Branch, May 18, 1940. Honorable mention was made of the paper "A New Device for Slip Determination" by W. R. Chynoweth (Enrolled Student) University of Missouri, which was presented at a joint meeting of the St. Louis Section and the Missouri School of Mines and Metallurgy, University of Missouri and Washington University Branches, May 17, 1940.

Awards being made by the various Districts for 1940 papers will be announced in future issues, as the information becomes available.

1941 Lamme Medal Nominations Due December 1

Special attention is directed to the fact that the names of Institute members who are considered eligible for the AIEE Lamme Medal, to be awarded early in 1942, may be submitted by any member in ac-

Future AIEE Meetings

Summer Convention
Toronto, Canada, June 16–20, 1941

Pacific Coast Convention
Yellowstone National Park, August 27–29, 1941

South West District Meeting
St. Louis, Mo., October 8–10, 1941

Southern District Meeting
New Orleans, La., December 3–5, 1941

Winter Convention
New York, N. Y., January 26–30, 1942

cordance with section 1 of article VI of the bylaws of the Lamme Medal committee, as quoted in the following:

The committee shall cause to be published in one or more issues of ELECTRICAL ENGINEERING, or of its successors, each year, preferably including the June issue, a statement regarding the "Lamme Medal" and an invitation for any member to present to the national secretary of the Institute by December 1, the name of a member as a nominee for the medal, accompanied by a statement of his "meritorious achievement" and the names of at least three engineers, of standing who are familiar with the achievement.

Each nomination should give concisely the specific grounds upon which the award is proposed, and also a complete detailed statement of the achievements of the nominee to enable the committee to determine its significance as compared with the achievements of other nominees. If the work of the nominee has been of a somewhat general character in co-operation with others, specific information should be given regarding his individual contributions. Names of endorsers should be given as specified in the foregoing quotation.

1941 Year Book Issued

The 1941 edition of the AIEE Year Book has been issued, in accordance with 1940–41 budget provisions. Addresses are corrected as of February 28, 1941. Copies have already been distributed to all national, District, and Section officers, Student Branch counselors, and all members of national committees. Other members desiring copies may obtain them by writing to the AIEE order department, 33 West 39th Street, New York, N. Y. The Year Book is not available to nonmembers of the Institute, nor is its use permitted for commercial, promotional, or other circularization purposes.

Section • • • •

Institute Groups Hear English Engineer

T. R. Scott, chief engineer, power cable division, Standard Telephones and Cables, Ltd., London, Eng., addressed the power group of the AIEE New York Section, New York, N. Y., April 29, 1941, the round-table group of the Michigan Section, Detroit, Mich., May 2, and a round-table conference of the Edison Electric Institute, AIEE Chicago Section, and Commonwealth Edison Company, Chicago, Ill., May 5. Mr. Scott discussed technical advances in the use of Styrene, a new insulating material being used for emergency repairs in power-cable installations damaged by air raids, which he has demonstrated before representatives of power companies in various American cities.

Mr. Scott's trip to the United States has been arranged by International Standard Electric Corporation, supply and manufacturing division of International Telephone and Telegraph Corporation, of which Standard Electric is the principal British associate, with special permission of the British Government.

Branch • • • •

Third District Students Meet at Rutgers

With a reported total of 320 persons in attendance, the 15th annual student convention of the Institute's third District was held April 24, 1941 at Rutgers University, New Brunswick, N. J. A busy full day's program provided for the presentation and discussion of 7 student technical papers during the morning session, a variety of inspection trips to near-by points of technical interest during the afternoon, and an informal banquet in the evening.

The technical program included the following papers:

"Vacuum Tube Constants by Oscillograph." Loebe Julie, College of the City of New York

"Generation and Application of Square Waves." Gabriel Blechman, New York University

"An Electronic Frequency Meter." Rudolph Dehn, Newark College of Engineering

"Electric Power Requirements for National Defense." George Gilmore, Pratt Institute

"The Barkhausen Effect in Ferromagnetism." Edward Barlow, Cooper Union

"Design and Construction of a Vacuum-Tube Voltmeter." A. J. Dolan, Brooklyn Polytechnic Institute

"Synthesis of Electric Wave Shapes by Electronic Means." Burton R. Lester, Rutgers University

A special jury consisting of Allen B. DuMont, president, DuMont Laboratories, Passaic; T. M. Hunter (A'15, M'28) president, American Transformer Company, Newark; Robert B. Litchfield, (A'17) equipment engineer at New Jersey Bell Telephone Company, Newark, awarded a first prize of $25.00 to Mr. Blechman, a second prize of $10.00 to Mr. Lester, and honorable mention jointly to Mr. Dehn and Mr. Dolan. The judges themselves contributed a purse of $10.00 to be divided between the winners of honorable mentions, because of the closeness of the competition.

R. C. Muir (A'08, F'36) vice-president in charge of engineering for the General Electric Company, revealed the depth of his interest in student engineering activities by taking time out of his busy schedule to serve as the feature speaker for the general banquet. In speaking on the topic "The Electrical Engineeer in Industry," Mr. Muir briefly reviewed the nature and significance of the more important electrical engineering developments, stressing both the technical and the human or sociological aspects. In fact, he laid special emphasis upon the latter, defining the difference between a technician and a professional engineer in terms of the balance achieved by the individual between a knowledge of purely technical matters on the one hand and an understanding of human relationships on the other hand. Mr. Muir ventured the suggestion that a fully successful career as a professional engineer and citizen might very well require a foundation comprising something like 25 per cent good technical education and as much as 75 per cent in knowledge and understanding of human relations.

Guests of Honor at the banquet in addition to Mr. Muir included Dean P. H. Daggett of the college of engineering, Rutgers; Student Branch Counselor Frederic P. Fischer of Rutgers University; President Robert C. Clothier of Rutgers University; National Secretary H. H. Henline and Editor G. Ross Henninger from AIEE headquarters, New York; and Chairman J. F. Fairman of the New York Section. Mr. Fairman gave a particularly stimulating and challenging extemporaneous message to the students at the banquet, the essential substance of which is reflected in the transcript appearing on these pages under the title "Democracy, Like Charity, Begins at Home."

Democracy, Like Charity, Begins at Home

A Challenge to Students—and Others

"IF WE believe in our Code of Professional Ethics, let's live up to it, not just talk about it. Democracy, in the Institute, or in the nation, can't be made for us; we must make it. Let's really go to work for Democracy —which, like charity, begins at home; we can't afford to continue to 'let George do it', as the classic phrase goes." So challenged Chairman J. F. Fairman of the New York Section in speaking before a group of some 300-odd Enrolled Students at the recent AIEE District 3 student convention at Rutgers University. The essential substance of his thought-provoking extemporaneous comments is reflected in the following approximate transcript.

INSTITUTE LOOKS TO YOUTH

It has been my good fortune to have attended a number of these student conventions in recent years, and I always come away wondering why the members of the Institute, as they grow older, can't retain some of the spontaneity and enthusiasm which characterizes these Student Branch activities.

Heretofore, my presence has not been sufficiently official to afford me an opportu-

nity to speak to the gathering. Hence, I can't forego this long awaited chance to relieve my mind of the burden of some thoughts that I have been storing. Perhaps something of what I say will stick with some of you and lead you to carry over more of your present enthusiasm and high ideals into your future work in the Institute and in your profession.

You will understand better what is behind my wishful thinking for the future of the Institute in your hands when I tell you that, although the New York Section has nearly 3,500 members, your meeting with something over 300 in attendance is larger by far than three out of the four general Section meetings held this year. The bright spots in New York Section activities are the meetings sponsored by the five technical groups and I ascribe this to the fact that these groups were organized by, for, and of the younger element. They were designed to give the young engineers a forum for the exchange of ideas and experiences in the fields of their special interests and they are doing so good a job and are having such interesting meetings that the older men are attending them in preference to the general Section affairs. In my opinion, this is all to the good and I believe the time is not far distant when the youth movement will take over the Section itself and show the elder statesmen how to run it as it should be run.

Some of the other large Sections throughout the country have similar divisions of their work, adapted to the interests of their members. Wherever you may be located when you leave school and get a job, go to the local Section meetings, find out how the work is organized, and volunteer for service in whatever activity interests you, or whatever activity seems to need your help. Don't wait to be asked. You probably won't be. Volunteer.

WHAT IS DEMOCRACY?

This brings me to the next thought. Most of you are shortly going to be handed a tin hat and a gun and taught how to do squads right, or whatever its modern equivalent is, in order to prepare you, if need be, to help defend Democracy. Maybe you know what Democracy is. I hope you do, and that you think it is worth defending. Perhaps some of you have been wondering a bit, as many of us who went through the same motions some 20-odd years ago have been wondering, just what it's all about. Just what is this Democracy we talk about so glibly? How do you get it and, more important, how do you *keep* it?

Make no mistake about this—I shall not presume to tell you, because I am not sure that I know. Nevertheless, I am quite sure that some of the things done in its name are not democratic, and indeed definitely bear the earmarks of a type of political philosophy we are supposed to be "neutral against". I shall give you just one concept that I keep coming back to in my own thinking. If it appeals to you as a foundation stone, you might build on it.

To me, Democracy implies that each of us to the full extent of his time and ability and taking into account his special talents, does his share in promoting the common welfare of every group of which he is a part or with which he is connected directly or indirectly. To me, Democracy, like charity, literally begins at home. It begins in the family group, the school, the college, the Student Branch and the Section of the Institute, the fraternal organization, the club, the various civic and charitable organizations, the church, and in all the other organized activities of a community. If, working together, we can make a success of such activities, it should be easy to make Democracy work in the broader fields of state and national affairs; yes, even in the very broad field of international affairs. If we can't or won't, then in my opinion we shall lose this thing called Democracy and we shall deserve to lose it.

WHY "LET GEORGE DO IT"?

If I am anywhere near right in this, my understanding of Democracy and the democratic process, I believe we have not far to go to find the reason for our present fears that our democratic system is in danger. We and many other people have not been working at it. We have largely "left it to George," and George has been a very busy man. Being busy, he had to take some shortcuts. Also, since nobody stopped him, he has been trying out some ideas of his own and naturally enough, they were principally directed to the greater glory of George. We can't blame George. He probably did the best he could. Unfortunately, we don't like the results and certainly we don't like George as well as we did.

I think we have been lazy in passing the buck to George on important matters of public interest. I think we should actively carry our own individual and definite responsibilities of citizenship.

Are you fellows going to play golf on Election Day, all day, as so many of your elders have done, in the mistaken and lazy belief that "one vote more or less won't make any difference to anybody?" Are you going to crab about how the Institute is run, and do nothing about it but crab. Are you going to stay away from church, asserting that it is full of hyprocrites who would taint your pure souls? Are you—but why go on? You have to make your own answers, and you will have to live with the consequences of your action or inaction.

Just one more thought before I conclude these rambling remarks. It seems that one school of thought assigns to technology (and that means engineers) the blame for the dislocation of our economic system. Before I got to thinking about George and his place in the scheme of things, that allegation used to annoy me very much. I was sure somebody else was to blame. Now I'm not so sure. Perhaps we have been leaving part of our job to George, and hence are partly responsible for the results.

Within the last few days, our AIEE editor asked me to review two papers, each presented by a distinguished member of the Institute before his Section. The two Sections are well separated geographically, but the authors are poles apart in thought and philosophy. Both papers were well written. I hope both will be published. But the thing that startled me wide awake was the radically different conclusions reached by these two distinguished gentlemen, starting with substantially the same facts.

What is wrong with our engineering processes when that can happen? I was brought up to believe, as an engineer—and I suppose your professors still so teach you—that if all the facts are in our possession, we should be able to reason to a sound and logical conclusion, and that generally only one real answer is possible. Of course, sometimes in mathematical processes the answers can be negative or imaginary, and in such instances you know how to interpret them or what to do with them. Apparently, in the case of these authors, the imaginary answers had too strong an appeal entirely to be resisted. Consequently, their conclusions were colored accordingly and very beautifully colored, too. But that's not the engineering process, that's the kind of special pleading that all too frequently characterizes political and other aspects of human affairs. Gentlemen, as engineers, let's leave such specious special pleading to others. Let's content ourselves with being honest.

After reading those papers, I looked up our Code of Principles of Professional Conduct. Like these authors, I hadn't read it recently either. I want to read you a few selected paragraphs from that code:

"In all of his relations the engineer should be guided by the highest principles of honor.

"The engineer should endeavor to assist the public to a fair and correct general understanding of engineering matters, to extend the general knowledge of engineering, and to discourage the appearance of untrue, unfair, or exaggerated statements on engineering subjects in the press or elsewhere, especially if these statements may lead to, or are made for the purpose of, inducing the public to participate in unworthy enterprises.

"It is unprofessional to give an opinion on a subject without being fully informed as to all the facts relating thereto and as to the purposes for which the information is asked. The opinion should contain a full statement of the conditions under which it applies.

"An engineer in responsible charge of work should not permit nontechnical persons to overrule his engineering judgments on purely engineering grounds."

I submit that such a code has something vital to do with Democracy. If we believe in it, if we have any pride in and respect for our profession and ourselves, let's not just talk about these principles, let's have the courage to live up to them.

Conference on Student Activities Held by District 6 at Denver

The 14th annual conference on student activities of AIEE District 6 was held at the University of Denver, Denver, Colo., April 18–19, 1941. Nine colleges and universities were represented at the conference, which had a total registration of 124 students and faculty members. The program included a dinner meeting with the AIEE Denver Section at which President R. W. Sorensen, District Vice-President A. L. Turner, and Doctor J. M. Gage, University of Colorado, were speakers; two technical sessions; business meetings of Branch counselors and Branch chairmen; and a final session at which President Sorensen was speaker and District prizes for papers were announced.

The business meeting of counselors voted to hold the 1942 conference at Colorado State College, Fort Collins, on April 24 and 25. The conference was previously scheduled to be held at South Dakota State School of Mines, Rapid City, but a change was requested by Professor J. O. Kammerman, counselor of that Branch, who is

absent because of military service. Professor F. B. Beatty, Colorado State College, was elected chairman of the District committee on student activities and counselor delegate to the 1941 summer convention. Professor H. S. Rush, North Dakota State College, was selected as alternate counselor delegate.

At the technical sessions, the following student papers were presented:

A METHOD OF MAGNETIZING SMALL PERMANENT MAGNETS, **J. D. Smith** and **Art Siegal**, University of Denver.

AUDIO CONTROL OF COLOR, **F. A. Olson** and **H. B. Hansen**, University of North Dakota (presented by Robert Smith)

FREQUENCY RESPONSE AND EFFICIENCY MEASUREMENTS OF A LOUDSPEAKER, **F. H. Slaymaker**, University of Nebraska

AIRWAYS RADIO RANGES, **Sam Phillips**, University of Wyoming

AMATEUR TELEVISION, **Robert Barthlo** and **Vincent Winters**, South Dakota State College

APPLICATION OF THE AMPLIDYNE AS A VOLTAGE REGULATOR, **W. C. Brown** and **R. H. West**, University of Colorado

GIORGI MKS SYSTEM OF UNITS, **Dean Hendrix**, Colorado State College

AN INVESTIGATION OF GRID AND PLATE CURRENTS IN THE FG-67 THYRATRON, **Richard Nelson**, South Dakota School of Mines

EFFECTS OF ELECTRICITY ON THE HUMAN BODY, **Gus Stroebel** and **Allen Barstad**, North Dakota Agricultural College.

District prize for Branch paper was awarded to F. H. Slaymaker. W. C. Brown and R. H. West received first honorable mention, and J. D. Smith and Art Siegal second honorable mention.

Abstracts • • •

TECHNICAL PAPERS are previewed in this section as they become available in advance pamphlet form. Copies may be obtained by mail by remitting price indicated to the AIEE order department, 33 West 39th Street, New York, N. Y.; or at five cents less per copy if purchased at AIEE headquarters or at AIEE convention or District-meeting registration desks.

The papers previewed in this issue will be presented at the AIEE summer convention, Toronto, Canada, June 16–20, 1941.

Basic Sciences

41-107—Analytical Methods of Solving Discrete Nonlinear Problems in Electrical Engineering; *E. G. Keller (M'40). 20 cents by mail.* More often than not, the nonlinear problems of electrical engineering arise from discrete physical systems and are usually reducible mathematically to the solution of systems of nonlinear total differential equations or to systems of nonlinear integral equations. Six independent methods of solving discrete nonlinear problems are given in this paper. Each is illustrated by means of an electrical-engineering problem. The illustrative examples employed pertain to a-c and d-c nonlinear circuits, reluctance-induction motors, hunting of and dynamic braking of synchronous machines. References to additional methods are given in the bibliography. The 100 references listed represent approximately ten per cent of the field, but many of the entries contain bibliographies on their respective fields.

41-105—Diode Rectifying Circuits With Capacitance Filters; *D. L. Waidelich (A'39). 25 cents by mail.* This paper presents the results of an investigation of the half-wave and full-wave rectifier circuits with a simple capacitance filter and using either high-vacuum or mercury-vapor tubes. An equivalent circuit is set up, such that when the tube is conducting, a mercury-vapor tube is represented by a constant voltage drop or a high-vacuum tube by a constant resistance. A detailed analysis of this circuit is carried through in the appendix, and it is found that the output characteristics depend upon three parameters. The results of this analysis are presented in the form of curves giving the angles at which the tubes begin conducting and cease conducting and also the d-c output voltage. For the more special case of no tube drop, curves of ripple voltage, maximum tube current, and tube inverse peak voltage are presented. The comparisons made between the calculated results and test results show very satisfactory agreements. It is shown that the curves given in the paper may be used in the design of rectifier circuits with capacitance filters.

Communication

41-130—ACO—Sound Recording for the Amateur; *A. L. Williams. 20 cents by mail.* Many fields of technical development have appealed to the amateur, with the result that their amateur activities therein have contributed materially both to the progress of the art and to their own personal pleasure. Amateur radio and photography are notable examples, and the recent increase in interest in home recording gives promise that this field is now ripe for amateur exploitation. Both magnetic and disk recording are particularly well adapted to amateur interest, but due to the present-time difficulty of obtaining component parts for magnetic-recording systems, the amateur is advised to concern himself first with disk recording, where all of the component parts necessary for constructing a high-quality machine are already available These component parts are discussed briefly. Disk material is considered, and some attention is given to recording characteristics suitable for amateur purposes.

41-129—The Measurement of Body Currents; *Robert S. Schwab. 15 cents by mail.* All living tissue has d-c potential differences between parts of different energy values. They are related to growth, metabolism, and the absorption of energy. Plants and all organs in animals show it. A-c potentials coming in distinct waves are found in tissues related to active motion. Muscle and nerves are electrically inactive except when stimulated. Heart is rhythmically electrically active in a special synchronous form. Brain and ganglion cells are continuously electrically active in an asynchronous way when healthy and awake; during sleep and in pathological states continuous synchrony develops. Death in all tissues is shown by total loss of both d-c and a-c potentials.

41-113—Radio Broadcasting in Canada; *A. Frigon (A'20). 15 cents by mail.* The development of radio broadcasting in Canada has been very rapid. There are now 85 broadcast transmitters in daily operation. All broadcasting is under the control of the Canadian Broadcasting Corporation, an independent government corporation, which in addition to its regulatory functions operates a coast-to-coast network connecting for a nation-wide service its own 10 modern stations with almost half of the privately owned transmitters. It cannot therefore be said that radio in Canada is owned and operated by the Government, as the CBC is independent and free to apply its revenues derived from licenses and commercial operation in the best interests of its radio audience. The Canadian system is one of co-operation between a semipublic service and private ownership. Parliamentary inquiries have always found it the best suited to Canada's needs considering its vast area and relatively sparse population.

41-111—ACO—Phonograph Record Recording and Reproducing; *A. D. Burt. 20 cents by mail.* For the second time during the history of the phonograph, public interest has reached such proportions that the resultant business has become of great commercial importance. Mechanical reproducing means were concerned with the first period and electrical reproducing means with the second period. Laterally cut disks have provided the principal form used for the phonograph record. Only such historical information is included as relates specifically to the laterally cut record and the reproducing means employed. Improvement in phonograph reproduction can be obtained by designing to minimize the more obvious defects such as "wow," flutter, rumble, surface noise, and "needle chatter". The wider the reproduced frequency range becomes, the more important it is to minimize these defects. The paper illustrates how the use of the analogy between mechanical and electrical circuits facilitates the solution of the complicated mechanical and acoustical problems in this field.

Electrical Machinery

41-126—Transient Torques in Squirrel-Cage Induction Motors, With Special Reference to Plugging; *E. S. Gilfilan, Jr. and Edward Kaplan. 30 cents by mail.* When a squirrel-cage motor is switched in any way, whether while running or at rest, transient torques, which are usually several times the steady-state torque, occur and must be considered in design. It was desired to obtain a general semiquantitative view of these torques by considering a limiting case which is accessible analytically, with the expectation that a simple rule would be apparent for estimating the magnitude of these torques from design data. No such rule was found, and we must be content to exhibit limiting transient torque curves for certain types of motors in the commercial range and to provide accurate formulas for calculating such limiting torques for types not considered here.

41-127—Excitation Circuits for Ignitron Rectifiers; *H. C. Myers and J. H. Cox (A'26). 20 cents by mail.* The excitation of ignitron rectifiers can be accomplished by a

considerable variety of circuits. After some experience the types used commercially have narrowed down to a few. The anode-firing method, though simplest, does not provide sufficiently positive excitation to produce a desirable degree of balance in the larger installations. Separate excitation systems have been developed which use capacitor impulses controlled with thyratron, rotating-impulse generators, and capacitor impulses controlled with saturating reactors. The capacitor-thyratron system has most flexibility of control but makes use of thyratrons which are a renewable item. The rotating-impulse generator is attractive only on large installations and here there is danger of system hunting. The saturating-reactor system constitutes a positive system which has no renewable parts. Means have been developed for either manual or automatic control.

41-124—A New Transformer for Base Load Stations; *Philip Sporn (F'30) and H. V. Putman (M'32). 15 cents by mail.* This paper describes the application of "Hipersil" to three 40,000 kva units for the Philo generating station of The Ohio Power Company. Because of "Hipersil's" ability to carry one-third more magnetic flux, appreciable savings in weight and dimensions are possible—in fact, the transformers will be shipped in oil completely assembled with bushings in place, ready to operate. Forced-oil and forced-air cooling is provided, with proper relays for protection in the event of excessive copper temperature or failure of auxiliaries. Reliability, economy, ease of installation, and low maintenance have been the objectives sought in the design.

41-118—The Basis for the Nondestructive Testing of Insulation; *R. F. Field (M'40). 20 cents by mail.* The success of the nondestructive testing of insulation depends on the existence of a satisfactory correlation between any decrease in dielectric strength caused by deterioration of any insulation and changes in the electrical characteristics of the insulation. Such correlation does exist because of the mutual dependence of dielectric strength and low-frequency interfacial polarization on the abundance and disposition of free electrons and ions throughout the material. This polarization is defined by four parameters whose values can be determined only from current-time curves because the relaxation frequency of the polarization is below the range of bridge measurements. The method of graphical analysis of these curves suggested by K. S. and R. H. Cole in a paper presented at a recent meeting of the American Physical Society, can be used for the calculation of these parameters.

41-110—Damping and Synchronizing Torque of the Double-Fed Asynchronous Machine; *M. M. Liwschitz (M'39). 15 cents by mail.* It has required more than 20 years (L. Dreyfus—1911, R. H. Park—1933) to solve the damping problem of the d-c-excited synchronous machine. In recent times the a-c-excited synchronous machine, that is, the double-fed asynchronous machine, has become important as drive with wide speed range. For speed control at least four more main machines are necessary, two synchronous machines and two d-c machines. The total system consists of mechanical springs, electrical springs (synchronizing torques), mechanical dampings, electrical dampings, and masses. The dynamic stability of the system depends on the springs, dampings, and masses of all parts of the system. At present no work has been published about the damping and synchronizing torques of the a-c-excited synchronous machine. The object of this paper is to derive formulas for these torques. As in the case of the synchronous machine, complicated results cannot be avoided. Approximate shorter formulas are given at the end of the paper.

Electronics

41-117—Current Rating and Life of Cold-Cathode Tubes; *G. H. Rockwood (M'34). 15 cents by mail.* The life of low-voltage cold-cathode tubes is found to be determined solely by the current drawn. Tube life is terminated by the removal of the active material from the cathode surface by sputtering. The relationship between life and current drain is established on theoretical grounds and this relation checked experimentally. The application of the law relating current and life to tube ratings is discussed.

Industrial Power Applications

41-98—A New Mercury Rheostatic Element for Regulation and Control; *K. A. Oplinger (M'39). 15 cents by mail.* See May issue, page 230, for abstract incorrectly numbered there as 41-99.

41-136—A Distribution System for War-Time Plant Expansion; *J. L. McKeever (A'32). 15 cents by mail.* This paper describes the industrial distribution system recently installed in an extension to the Peterborough, Ont., plant of the Canadian General Electric Company. Use is made of the network principle but the system is thought to be unique in that it is a development of the primary network propounded by various members of the General Electric Company some ten years ago, rather than of the metropolitan type of network. Use is made of unit substations of simplified design with Pyranol-filled transformers. The 6,600-volt primaries are connected into a loop or ring main, while the 575-volt secondaries are interconnected to form a network. The network protection is extremely simple and consists merely of the inverse-time and instantaneous trips on the 575-volt network air circuit breakers at either end of the 6,600-volt loop. Advantages obtained by the use of the network system are given and a comparison is made between it and the conventional radial system as regards both function and cost.

Instruments and Measurements

41-132—The A-C Dielectric-Loss and Power-Factor Method for Field Investigation of Electrical Insulation; *Frank C. Doble (A'12). 20 cents by mail.* This paper explains in detail the shielding principles which made field testing possible, traces the history of its development, and summarizes its application as already recorded in the literature.

41-125—Relative Accuracy of Three-Phase Metering Combinations; *C. T. Weller (M'21). 15 cents by mail.* This paper grades in terms of relative accuracy several three-phase combinations of instrument transformers and watt-hour meters under various conditions. The grades range from *A* to *E*, *A* being assigned to cases where the metering combination and the conditions of application represent the best standard practice, which ordinarily approximates the ideal. In a metering combination, this means resolvability into two or more component single-phase sections. The combinations are considered principally from the instrument-transformer standpoint. Sources of uncertainty or of error are discussed, emphasizing especially difficulties sometimes encountered with wye-connected potential transformers and the effects of various secondary interconnections on the metering accuracy. The paper is summarized in one tabulation, which conveys a general idea of the performance to be expected from the metering combinations under different conditions from the accuracy standpoint. Four figures show the schematic connections of complete metering applications and of the component parts.

41-112—The Shielding of Permanent Magnets From Transient Magnetic Fields; *George J. Wey (A'38). 15 cents by mail.* Operating experience with watt-hour meters has shown that the damping magnets on a few meters each year are weakened by the magnetic fields of lightning-surge currents which may flow in the service wiring. The paper shows how ordinary forged steel magnets may be protected from such fields by shielding with a thick copper coating applied by a new high-speed copper plating process. Curves are shown comparing the shielding effect of ordinary copper plating, Schoop sprayed copper, copper-clad magnet steel, and the new high-speed copper plating. Desirable features of this method of protection are complete interchangeability between shielded and unshielded magnets and the use of conventional materials which are easy to obtain.

41-108—An Improved Frequency Meter for Commercial Power Frequencies; *K. J. Knudsen (M'38). 15 cents by mail.* This paper describes a frequency meter in which the external reactor has been eliminated by using an iron core cross-coil dynamometer. Detailed description is given of a precision calibration method, accomplished by means of a multivibrator, an oscillograph, and a variable speed generator in conjunction with an auxiliary frequency meter, having a range of two-tenths cycle. The accuracy of the 55–65-cycles instrument is within two-tenths cycle, allowing for a voltage variation of 90 to 140 volts, a ten per cent third harmonic distortion, and ambient temperatures from minus 20 to plus 45 degrees centigrade. The dynamometer can be housed in a three-and-a-half-inch case and is well adapted for use as a six-inch instrument. It is felt that this frequency meter is of particular value where space is limited, due to its compactness and the absence of auxiliary equipment.

41-106—Effect of Sapphire Crystal Orientation on the Wear of Watt-Hour Meter Bearings; *J. H. Goss (A'35). 15 cents by mail.* This paper describes the most recent of a series of studies on the life of watt-hour-meter bearing materials. It covers an investigation of the effect of jewel crystalline axis orientation upon jewel wear. Lifetime stability of meter calibration is a function of bearing wear. A study of the wear (after several years' service) of the sapphire jewel cups of meters in relation to crystalline orientation confirms predictions of another investigator; and a corroborative theory, based upon the physics of crystals, is presented.

41-119—Power Circuit Instruments for the Higher Range of Audio-Frequencies; *L. J. Lunas (M'36) and Paul MacGahan (M'15). 15 cents by mail.* The extending use being made of frequencies from 900 to 12,000 for special purposes such as induction furnaces, introduces new problems in instrument design and calibration. Previous practical a-c instruments were either of the electrodynamic or moving-iron types designed for low power frequencies or thermal and rectifier types for audio- and radio-frequencies, these latter usually being confined to measurements of only current and voltage. The ordinary low-frequency electromagnetic instruments have such high coil reactance and losses that they are unsuitable for the higher power frequencies in question without special arrangements, which are described in the paper. Furthermore, the usual calibration methods and standards as previously used for low frequencies are not adequate, and therefore new methods of calibration were introduced.

41-120—Bushing Tests; *A. L. Brownlee (A'25) and W. H. Wickham (A'41). 15 cents by mail.* This paper gives the results of power-factor tests on high-voltage bushings at test voltages up to or above the operating voltage. The results show the desirability of testing at these higher voltages. The paper also describes the findings of laboratory examinations of deteriorated bushings from which considerable information has been obtained concerning bushing deterioration.

Land Transportation

41-104—Modern Motors Serve City Transit Systems; *W. J. Clardy (M'39) and C. A. Atwell (A'41). 15 cents by mail.* City transit motors operated today include many new mechanical and electrical features. Modern vehicles differ greatly from those of a decade ago and propulsion motors contributed substantially to the advances achieved. Meeting present-day needs has required designs for 300 and 600 volts involving extensive use of new materials, application to new types of drive, and suitability for dynamic braking. Mechanical design includes unusual developments in frame construction, method of mounting, lead arrangement, ventilation, housings, and bearings. Compactness has led to ingenuity in brushholder arrangement to secure accessibility. Armatures require judicious selection of materials for shafts, cores, and commutators, as well as special seasoning and balancing procedure. Electrical design betterments have been introduced in armature slots, armature coils, field coils, and insulation. Provision for quietness and good commutation are also salient points. The new designs have resulted in high electrical and weight efficiency for series motors used on Diesel-electric buses, trolley coaches, and street cars, in comparison with old type machines. Excellent commutation has produced outstanding stability at rapid accelerating and dynamic braking rates. Vehicle performance is exceptional with respect to safety, operating efficiency, available selection of accelerating and braking rates, and the broad speed-range of the dynamic brake.

Power Transmission and Distribution

41-131—Impulse Strength as a Measure of Cable Quality; *L. I. Komives (A'41). 20 cents by mail.* The results of impulse tests on impregnated-paper insulated cables seem to indicate that, in a cable having the best obtainable insulation, breakdown occurs at a voltage for which the maximum stress is around 3,300 volts per mil. If the quality of the insulation is inferior, owing either to nonuniformity of taping or incomplete impregnation, the maximum stress value becomes less than 3,300 volts per mil and, therefore, the maximum stress obtained from impulse tests is a good measure of the uniformity of taping and the degree of impregnation. Solid, oil-filled, oilostatic, and compression cables, when new, all should have the same maximum stress at breakdown. For a given insulation thickness, the oil-filled cable, having the largest conductor diameter, will withstand the highest voltage even after aging. Oilostatic and compression cables also are expected to retain their original breakdown values after aging. Because of the decrease of the degree of impregnation in service, aged solid cables have a lower impulse strength than new ones and therefore, taping, being independent of age, is more important than the degree of impregnation. Low gas pressure cables, although originally lower than solid-type cables, in regard to impulse strength, are expected to retain this value after aging.

Production and Application of Light

41-123—The Incandescent Lamp Situation From the Engineering Point of View; *Preston S. Millar (M'13). 25 cents by mail.* At the height of its career, the incandescent electric lamp occupies a place of large importance in which its numerous good qualities contribute to its usefulness. Lamp engineering seeks high efficiency and low cost of light production with consistency of lamp performance and simplicity of application. It grapples with numerous problems and makes selection between possible alternative procedures. Its criterion is satisfaction of the public in lighting matters. Data are presented to show qualities of lamps and aspects of performance with which lamp engineering procedure has to do. Attainments of the lamp industry are reviewed. Benefits of large-scale industry leadership are asserted. Achievements and the relative standing of the American lamp industry are discussed.

Protective Devices

41-137—Field Investigations of Lightning; *C. F. Wagner (F'40), G. D. McCann (A'38), and Edward Beck (M'35). 25 cents by mail.* See May issue, page 231, for abstract incorrectly numbered there as 41-100.

41-133—The Protection of Solid Insulation by Lightning Arresters; *D. D. MacCarthy (A'28) and T. J. Carpenter (A'38). 15 cents by mail.* An investigation has been made to determine the impulse failure voltage of oil-immersed paper insulation samples made from materials used in distribution transformers. Previous investigations had largely dealt with high-voltage insulation and 1.5×40 microsecond full waves or chopped waves, rather than with the wave shapes resulting from the operation of lightning protective devices. In the present investigation volt-time puncture curves were obtained from tests on the wave front that show the puncture voltage as a function of time for different thicknesses of insulation. These curves were found to be relatively flat. In part of these tests, the magnitude and wave shape of the voltage applied to the insulation was controlled by lightning arresters or protective gaps in parallel with the insulation. The effect of repeated shots was also investigated. Voltages in excess of approximately 70 per cent of the single shot failure voltage damaged the insulation.

41-134—Dielectric Strength of Oil for High-Potential Testing of Oil Circuit Breakers; *H. J. Lingal (A'33), W. F. Skeats (M'36), and H. D. Braley (A'18). 15 cents by mail.* This paper reports the results of work done by an AIEE working group assigned to determine the minimum dielectric strength of oil for high potential testing of oil circuit breakers. Data from many tests, both 60-cycle and impulse, are collected, tabulated, and analyzed. The data cover tests on both new oil and used oils and the results are used in drawing the conclusions and recommendations offered by the authors. The paper shows that the dielectric strength of oil circuit breakers does not vary in direct proportion to the strength of oil as measured in a test cup. Recommendations are made as to the dielectric strength of oil to be used for circuit breaker testing.

41-135—New Current Transformer for Bus Differential Protection; *L. F. Kennedy (M'39) and A. T. Sinks (A'36). 30 cents by mail.* During the past five years many studies have been made of means for providing reliable bus differential protection. Practically all of these studies have resulted in proposed methods of bus protection capable of overcoming current transformer errors. This paper describes a new current transformer developed particularly for application where high speed differential protection is required. Current transformers designed with an air gap in the core are shown to be capable of maintaining an essentially constant ratio even with the high primary currents flowing into near-by external faults. With the possible error current due to current transformer differences reduced to a small percentage of the total current a reliable simple relay system is capable of distinguishing easily between internal and external faults. These air-gap

core transformers are shown to be much smaller than conventional designs for the same performance.

41-128—Protection of Low-Voltage Circuits by Air Circuit Breakers in Cascade Arrangement; *A. E. Anderson (F'40) and C. H. Black. 25 cents by mail.* This paper outlines a new solution to the problem of providing adequate short-circuit protection for low-voltage circuits operating at 600 volts or less. There are many instances where a relatively large number of main feeder circuits supply an even larger number of branch feeders. The selection of branch feeder breakers, or possibly even main feeder breakers, with interrupting ratings high enough to match the obtainable short-circuit currents may prove completely impractical when viewed with any reasonable regard for space requirements or cost. The paper describes a practical and economical solution to this problem. Air circuit breakers of varying interrupting ratings but properly coordinated designs are used in a "cascade" or series connection in such manner that in event of a severe fault, the main breakers "back up" the smaller main feeder breakers, and these in turn "back up" the branch feeder breakers.

41-115—Lightning to the Empire State Building—II; *K. B. McEachron (F'37). 20 cents by mail.* Since 1935 the author has been trying to secure oscillographic records of the wave shapes of natural lightning to the Empire State Building. The first low-speed oscillogram showing changes in current during one second was obtained in 1937. Four usable high-speed oscillograms of current peaks were obtained in 1938, including 12 oscillograms showing 12 peaks occurring in 0.28 second. During the summer of 1940, 17 strokes were recorded on the low-speed oscillograph and correlating data were obtained for most strokes on the high-speed oscillograph. Forty-one current peaks so recorded make possible the determination of the frequency of occurrence of various rates of rise, crest currents, duration, and charge. One stroke having a positive crest current of 58,000 amperes was recorded. The application of these data to transmission lines is briefly discussed.

41-116—Power Circuit Breaker Ratings; *R. C. Van Sickle (M'37). 15 cents by mail.* Circuit-breaker application is being simplified. An important step in this movement is the establishment of the various elements of a breaker rating in such relation to one another that the choosing of a breaker of adequate interrupting capacity automatically selects a breaker capable of meeting the other related requirements. A new proposal for the calculation of the interrupting current eliminates the variable of the tripping time of the circuit breaker. This paper shows that with the standardizing of the tripping time, the rated making current, rated momentary current, rated five-second current and rated interrupting capacity can be related to simplify further the breaker application.

41-114—Mechanical Simplicity of Air-Blast Circuit Breakers; *H. W. Haberl (A'28) and Otto Jensen. 15 cents by mail.* This paper deals with the mechanism of air-blast breakers. Included is a general description of breakers with voltage ranges from 4 to 230 kv followed by a detailed description of some of the mechanism common to all types. Three distinct types of breakers are followed through a sequence operation and schematic diagrams are included to clarify the mechanical details. Included in the diagrams are photographs of the actual breaker being described, also a sequence oscillogram and a staged interruption test. A fourth type of breaker is described, but schematic diagrams of this type are not included as they are similar to one of the previous types.

41-122—D-C Machine Flashover and Bus Short Circuit Protection; *T. B. Montgomery (M'41) and J. F. Sellers (A'34). 25 cents by mail.* In protecting d-c bus systems recognized tripping methods which have been generally accepted are reviewed. Two methods of bus construction for large d-c steel-mill applications having large concentration of power, and reasons for their justification are presented. Bus construction of two typical large hot-strip mill applications are described. Test oscillograms and characteristic test curves for both heavy and nominal short-circuit interruptions are given for air circuit breakers protecting these systems in the conventional manner. D-c machine characteristics are developed under short-circuit conditions and formulas and short-circuit current curves are presented. A novel protective relay system which has proved successful in practice is described, and the improved protection indicated by tripping current and time values are shown in curve form.

41-121—System Short-Circuit Currents—Proposed New Calculating Procedure for Application of Interrupting Devices and Relays; *W. M. Hanna (A'26), H. A. Travers (A'41), C. F. Wagner (F'40); C. A. Woodrow (M'41) and W. F. Skeats (M'36). 20 cents by mail.* This paper is the report of a group assigned to investigate the problem under the auspices of the subcommittee on circuit breakers, switches, and fuses of the AIEE protective devices committee. The method proposed consists of the determination of the highest value of symmetrical short-circuit current for any type of fault as obtained by dividing voltage by subtransient reactance. Multiplying factors are then assigned according to the basis of rating of the equipment concerned and the speed of its operation. This procedure is more realistic in its appraisal of the contribution of the d-c component than the present decrement curves and with the increase in complexity of systems over recent years and the present wide and increasing use of high-speed relaying offers other advantages, both in simplicity of application and accuracy.

Personal • • •

A. J. Duncan (A'09) formerly president of the Texas Electric Service Company, Fort Worth, has been made chairman of the board of directors. **J. B. Thomas** (M'28) formerly vice-president and general manager of the company, has been appointed president and general manager. Mr. Duncan was born in 1877 at Pittsburgh, Pa. After having been employed for several years by the Cleveland Electric Illuminating Company, the Brush Electric Company, and the General Electric Company, he became lighting engineer for the Interborough Rapid Transit Company, New York. He was with that company for five years and about 1906 was made secretary and general manager of the Citizens' Railway and Lighting Company of Fort Worth. About 1915 he became president of the Fort Worth Power and Light Company, and in 1932 was made president of the Texas Electric Service Company. Mr. Thomas was born July 19, 1891, in San Marcos, Texas, and received the degree of bachelor of science in mechanical engineering from Texas Agricultural and Mechanical College in 1911. In 1912 he became a draftsman and engineer for the Texas Power and Light Company, and in 1916 was made resident engineer in charge of construction. From 1916 to 1917 he was office engineer for that company. From 1917 to 1919 he served in the United States Army Coast Artillery Corps, and returned to the Texas Power and Light Company as resident engineer and later as assistant to the chief engineer. From 1921 to 1929 he was chief engineer for the company and in 1930 became vice-president in charge of operations for the Texas Electric Service Company, later occupying the positions of executive vice-president and general manager. He has been active on several Institute committees, and is also a member of The American Society of Mechanical Engineers.

A. P. M. Fleming (M'14, F'34) director of research and education, Metropolitan-Vickers Electrical Company, Ltd., Manchester, England, and local honorary secretary of the Institute for Great Britain, has been awarded the Faraday Medal for 1940 by the Council of the Institution of Electrical Engineers (Great Britain). Doctor Fleming was born January 16th, 1881, at Newport, Isle-of-Wight, and received the degree of master of science from Finsbury Technical College, London, in 1898. In 1898 he became assistant engineer of the London Electric Supply Corporation, and later carried on experimental testing for Elliott Brothers, electrical instrument makers. From 1900 to 1902 he was with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and from 1902 to 1905 was insulation specialist for the British Westinghouse Electric and Manufacturing Company, Ltd., Manchester, England, which subsequently became Metropolitan-Vickers Electrical Company, Ltd. In 1905 he became transformer designer for the company, and in 1908 assistant superintendent in charge of manufacture and design of transformers. He was made superintendent of the transformer, winding and insulating department in 1911 and became director of research and education in 1914. In 1915 he was sent to the United States by the British government to make an investigation of American institutions organized to conduct industrial research. Doctor Fleming is the author of several books and of many technical articles, and holds the honorary degrees of master of science, Manchester, and doctor

of engineering, Liverpool. He is a past president of the Institution of Electrical Engineers, and is a fellow of the Institute of Patentees and a member of the Institution of Mechanical Engineers.

F. D. Knight (M'25) formerly superintendent of production for the Boston Edison Company, Boston, Mass., has become assistant to the operating vice-president of the Hartford (Conn.) Electric Light Company. **H. W. H. Wellington** (A'38) formerly assistant superintendent of production, will succeed Mr. Knight as superintendent of production for the Boston company. Mr. Knight was born in Limerick, Maine, October 27, 1883, and received the degree of bachelor of science in electrical engineering from the University of Maine in 1909. From 1909 to 1925 he was superintendent in charge of construction for projects undertaken by the Stone and Webster Company of Boston, Mass., in Fort Worth, Tex., Baton Rouge, La., Boston, Mass., Springfield, Mass., and Hartford, Conn. In 1925 he became superintendent of the generating department, Edison Electric Illuminating Company of Boston (now Boston Edison). He is also a member of The American Society of Mechanical Engineers. Mr. Wellington was born June 23, 1890 in Boston, Mass. In 1911 he became associated with the General Electric Company, at Lynn, Mass., and worked in several departments before joining the Stone and Webster Company, Boston, Mass., as a construction wireman. He later worked as a draftsman for the Boston Elevated Company and was also with the Edison Electric Illuminating Company of Boston in the technical division for a short time. After working with the American Car Works of St. Louis, Mo., and the Union Electric Light and Power Company of St. Louis he joined the Edison Electric Illuminating Company of Boston in 1921 as electrical technical engineer. In 1924 he became assistant to the superintendent of the production department, and in 1937 was made assistant superintendent of production.

Wilfred Sykes (A'09, F'14) formerly assistant to the president of the Inland Steel Company, Chicago, Ill., has been elected president of the company. Mr. Sykes was born in Palmerston, North New Zealand, December 8, 1879, and attended the University of Melbourne. From 1900 to 1905 he was employed by D. Durcks and Company (afterwards Knox-Schlapp and Company), Australian agents for Allegemeine Elektricitats Gesellschaft of Berlin, Germany. He was assistant to the chief engineer, manager of the Sidney branch, and later chief electrical engineer for the concern in Melbourne. When the Allegemeine Elektricitats Gesellschaft agency was transferred to Staerker and Fischer he took charge of electrical work in Victoria, Tasmania, and South Australia, and in 1906 went to Berlin as engineer in the foreign department of the Berlin company. In 1909 he came to the United States and was employed as engineer by the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. In 1921 he became affiliated with the Steel and Tube Company of America, Chicago, Ill., and in 1923 joined the staff of the Inland Steel Company. He was a manager of the Institute from 1917 to 1921, and has been active on several Institute committees. He is also a member of The American Society of Mechanical Engineers and the American Institute of Mining and Metallurgical Engineers, and is the author of several technical papers.

W. F. Grimes (A'19, M'27) radio material officer of the 11th Naval District, San Diego, Calif., has been promoted to the rank of lieutenant-commander in the United States Naval Reserve. Mr. Grimes was born in Pasadena, Calif., February 21, 1895, and studied electrical engineering at the University of Southern California. From 1917 to 1918 he was with the staff commander-in-chief of the United States fleet, working on maintenance of communication equipment. In 1918 he became assistant in the Naval Radio Research Laboratory at the Bureau of Standards, Washington, D. C. From 1919 to 1924 he was expert on radio for the bureau of engineering, Navy Department, Washington, D. C. In 1925 he joined the Westinghouse Electric and Manufacturing Company, and did sales and engineering work for the Los Angeles, Calif., office. From 1931 to about 1936 he was engaged as radio interference engineer for various Los Angeles trade associations, and in 1936 became chief engineer (later manager) of the Radio Interference Engineering Bureau of Los Angeles. During 1941 he has been serving as radio material officer in the United States Naval Reserve. He is the author of numerous technical publications.

C. E. Brown, Jr. (A'40) formerly assistant to the president of the Okonite Company and the Okonite-Callender Cable Company, Washington, D. C., has been elected vice-president of the companies. He will also remain in charge of the Washington, D. C., office. Mr. Brown was born August 2, 1894 in Buffalo, N. Y., and received the degree of bachelor of arts from Princeton University in 1917. From 1919 to 1925 he was with the Central Electric Company, Chicago, Ill., and during 1925 was country sales manager in charge of sales in about 19 states outside Illinois. In 1925 he became affiliated with the Okonite Company, as manager of the power and light department in the Chicago area. In 1930 he was transferred to the executive offices of the company in New York, and became executive assistant to the president. Since 1934, in addition to retaining the latter position he has been sales executive for the company in Washington, D. C. He is also a member of the American Society of Naval Engineers.

W. H. Pratt (A'02, F'13) retired consulting engineer of the meter division of the General Electric Company, Lynn, Mass., has been chosen as the first recipient of the New England Award newly established by the Engineering Societies of New England, Inc. Mr. Pratt was born December 29, 1872, at Waltham, Mass. He received the degree of bachelor of science in electrical engineering from the Massachusetts Institute of Technology in 1894, and shortly afterward was employed by the Judson L. Thompson Manufacturing Company of Waltham, Mass., as a draftsman. In June 1895 he entered the testing department of the General Electric Company, at Lynn, Mass., and in November of the same year was appointed foreman in charge of the standardizing laboratory. In 1897 he became assistant in meter and instrument design in the engineering department of the company, and later was made designing engineer in charge of meter and instrument design. He is the owner of several patents.

F. B. Jewett (A'03, F'12) president of the National Academy of Sciences is a member of the board of the newly created National Science Fund of the National Academy of Sciences (see page 308). Doctor Jewett who is a vice-president of the American Telephone and Telegraph Company, New York, N. Y. and chairman of the board of directors of the Bell Telephone Laboratories, is serving as a member of the National Defense Research Committee. Other Institute members who will serve on the board of the National Science Fund are **K. T. Compton** (F'31) president of the Massachusetts Institute of Technology, Cambridge; **Gano Dunn** (A'91, F'12) president of the J. G. White Engineering Corporation, New York, N. Y., and chairman of the advisory power committee organized by the National Defense Advisory Commission; and **R. A. Millikan** (M'22) director of the Norman Bridge Laboratory of Physics and chairman of the executive council of California Institute of Technology, Pasadena.

J. B. Noe (A'03, F'30) assistant to the planning engineer of the Consolidated Edison Company of New York, Inc., New York, N. Y., retired recently after 43 years with the company. He was born in Elizabeth, N. J., March 27, 1876, and received the degree of bachelor of science from Rutgers University in 1897. From 1897 to 1901 he was employed as a meter tester by the Edison Electric Illuminating Company (now the Consolidated Edison Company of New York, Inc.), and for a year was also electrical engineer of the Consolidated Telegraph and Electrical Subway Company. In 1902 he became assistant to the superintendent of transmission and distribution of the Consolidated Edison Company, and in 1910 was made assistant to the chief electrical engineer. He became assistant engineer of the electrical engineering department in 1925. He is also a member of the American Standards Association.

H. L. Hazeltine (A'20, F'40) engineer of insulation for the Sterling Varnish Company, Haysville, Pa., has been elected vice-president of the company. Mr. Hazeltine was born May 26, 1891, at Miller Place, N. Y. He received the degree of bachelor of philosophy from Yale University in 1913, and from 1913 to 1915 was assistant instructor in physics in the Sheffield Scientific School of Yale University. After a year as foreman for the White Adding Machine Company, New Haven, Conn., he became instructor in physics at the Georgia School

of Technology, Atlanta, in 1916. In 1917 he became head of the department of electricity of the School of Industrial Arts, Trenton, N. J., and in 1920 became affiliated with the Sterling Varnish Company, as eastern manager. From 1923 to the present he has been engineer of insulation for that company. He is also a member of the American Society for Testing Materials.

F. S. Bacon, Jr. (A'37) formerly sales engineer for the central station division of the Westinghouse Electric and Manufacturing Company at Boston, Mass., has been appointed assistant central station manager, New England district. **F. R. Benedict** (A'40) has been made engineering manager for the New England district, and **L. O. Dorfman** (A'19, M'28) formerly engineering manager for the New England district has been appointed assistant to the district engineering manager at East Pittsburgh, Pa. **C. F. Herbold** (A'33) formerly engineer of the small motors division, is now manager of industrial relations for the small motors division. **S. C. Leyland** (A'40), who was relay application engineer for the company, has been made relay section engineer for the meter division, and **R. M. Smith** (A'35) formerly section engineer, is now manager of the engineering department of the wiring device division.

C. J. Grece (A'22) assistant general foreman in the underground division of the Consolidated Edison Company of New York, Inc., New York, N. Y., has retired, having been with the company for 40 years. Mr. Grece was born in Jersey City, N. J., September 5, 1884. He joined the Consolidated Edison Company in 1900, and has served since as underground helper, tester, foreman, and assistant general foreman.

C. I. MacGuffie (A'27) has been appointed manager of sales, electric welding section, industrial department, General Electric Company, Schenectady, N. Y. He was formerly assistant manager.

R. C. Glancy (A'18, M'26) formerly operating results engineer, has been appointed general staff engineer, Bell Telephone Company of Pennsylvania, Philadelphia, Pa.

Obituary • • •

Morton Githens Lloyd (A'08, M'10, F'12) chief of the safety codes section at the National Bureau of Standards, Washington, D. C., died April 26, 1941. He was born September 10, 1874, in Beverley, N. J. He received the degrees of bachelor of science, 1896, doctor of philosophy, 1900, and electrical engineer, 1908, from the University of Pennsylvania. He also studied at Harvard University and the Friedrich Wilhelms Universitat, Berlin. From 1899 to 1902 he was an instructor in physics at the University of Pennsylvania, and in 1902 became associated with the Bureau of Standards, where he served first as laboratory assistant and later as assistant physicist and associate physicist. He was technical editor of the *Electrical Review and Western Electrician*, Chicago, Ill. from 1910 to 1916. In 1917 he returned to the Bureau of Standards as associate electrical engineer. He was the author of several technical articles and of many of the technical publications of the Bureau of Standards. In 1910 he received the Edward Longstreth Medal of the Franklin Institute. He was president of the International Association of Electrical Inspectors, past president of the American Society of Safety Engineers, and was also a member of the United States National Committee of the International Commission on Illumination, the National Fire Protection Association, the National Safety Council, and the American Standards Association. He served on the Institute committee on safety and was a past chairman of the Washington Section.

William Shirley Richhart (A'08, M'13) superintendent of power production at the Spy Run generating plant of the Indiana Service Corporation, Fort Wayne, Ind., died April 9, 1941. He was born September 26, 1881, in Noblesville, Ind. and received the degree of bachelor of science in electrical engineering from Purdue University in 1905. After having been employed by the Allis-Chalmers Manufacturing Company, Cincinnati, Ohio, for a short time, he did research work at Purdue University, Lafayette, Ind., and in 1906 became an instructor in electrical engineering at the University of Pennsylvania, Philadelphia. From 1911 to 1916 he was with the Westinghouse Electric and Manufacturing Company as an engineer in the service department, and in 1916 became affiliated with the Public Service Commission of Indiana, Indianapolis. In 1917 he joined the Indiana Service Corporation as an electrical engineer in the light and power department. He subsequently served as assistant operating engineer, power operating engineer, electrical distribution engineer and power production engineer. From 1935 to 1938 he was sent on leave of absence to do special engineering work in Indianapolis and New York. He was also a member of The American Society of Mechanical Engineers.

Roscoe Schaeffer (A'32, M'36) superintendent of engineering for the Oklahoma Gas and Electric Company, Oklahoma City, Okla., died April 18, 1941. He was born April 10, 1892, at Ludlow, Illinois, and received the degree of bachelor of science in electrical engineering from Iowa State College in 1915. From 1915 to 1916 he was assistant superintendent of a municipal steam-electric power plant at Buffalo Center, Iowa, after which he became associated with the General Electric Company, Schenectady, N. Y., doing work in the testing department, and in 1919 was made assistant to the general foreman of the General Electric testing department. From 1919 to 1923 he did electrical engineering work with the Remy Electric Company, Anderson, Ind., and with the William A. Baehr organization, Chicago, Ill. In 1923 he joined the Oklahoma Gas and Electric Company, Oklahoma City, as assistant to the construction superintendent and later became assistant to the general superintendent of operation. In 1926 he was employed by the Byllesby Engineering and Management Corporation of Chicago, Ill., continuing as resident electrical engineer on property of the Oklahoma Gas and Electric Company at Oklahoma City. In 1936 he was re-employed by the latter company as superintendent of engineering. He was vice-chairman of the AIEE Oklahoma City Section.

Reuben E. Nyswander (M'22) dean, school of science and engineering, University of Denver, Denver, Colo., died April 8, 1941. He was born January 4, 1878, in Antwerp, Ohio, and received the degrees of bachelor of arts, 1901, and master of arts, 1904, from Indiana University, and the degree of doctor of philosophy from Cornell University in 1908. From 1898 to 1903 he was an assistant in physics at Indiana University, Bloomington, and 1903–06 magnetic observer for the United States Coast and Geodetic Survey. He became an instructor in physics at Indiana University in 1908. After a year there he accepted a position as professor of physics at the University of Denver. In 1919 he was made director of the school of electrical engineering, and when it was reorganized into a combined school of science and engineering he became associate dean of the department. He was made dean of the school in 1937. Dean Nyswander was the author of several technical articles, and had invented a polarization photometer. He was chairman of the AIEE Denver Section, 1931–32.

Andrew Patterson (A'08, M'38) chief engineer of the Southwestern Gas and Electric Company, Shreveport, La., died April 4, 1941. He was born June 6, 1881, in Baltimore, Md., and was educated at Baltimore Polytechnic Institute. From 1903 to 1905 he was engaged in plant and distribution system redesign and reconstruction for H. M. Byllesby and Company, Chicago, Ill., and for the Oklahoma Gas and Electric Company, Oklahoma City. In 1905 he was electrical engineer in plant layout for the Muskogee Gas and Electric Company, and electric superintendent of layout construction sponsored by H. M. Byllesby and Company at Fort Smith, Ark. In 1914 he became engineer on electric plant construction for the Dawes Electric Company, later the Southwestern Gas and Electric Company, and was also electric superintendent, a position which he held until he was appointed chief engineer for the company in 1926.

Frederick John Cunningham (A'19) superintendent of communications, Consumers Power Company of Michigan, Battle Creek, died in April 1941. He was born February 28, 1886, in Saginaw, Mich. In 1911 he was employed by the Au Sable Electric Company, in constructing and operating a 140,000-volt line between Five Channels Dam and Flint, Mich. From 1912 to 1915 he was load dispatcher for the Au Sable Company at Saginaw, Mich., and in 1915 took charge of the eastern division of Consumers Power Company, which was formerly the Au Sable Company. After a year as division superintendent there, he was transferred to division superintendent of the southern division of the Consumers Power Company, at Battle Creek, a position which he held until his death.

Membership • •

Recommended for Transfer

The board of examiners, at its meeting on May 22, 1941, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Member

Adams, L. J., electrical engineer, Warner Brothers Pictures, Inc., Burbank, Calif.
Baker, B. P., development engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Bohn, D. I., electrical engineer, Aluminum Company of America, Pittsburgh, Pa.
Drake, D. K., assistant Montana transmission and protection engineer, Helena, Mont.
de la Serna, R. T., chief engineer, Cia de Electricidad del Sud Argentino, S. A., Buenos Aires, Argentina.
Deming, P. S., engineer, Oklahoma Gas and Electric Company, Enid.
Dickinson, R. C., section engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Diehl, R. P., electrical engineer, Park City Consolidated Mines Company, Park City, Utah.
Duff, C. K., meter engineer, Hydroelectric Power Commission, Toronto, Ont., Can.
Fleming, H. C., member of laboratory staff, Bell Telephone Laboratories Inc., New York.
Hagen, A. C., engineer, Rural Electrification Administration, Washington, D. C.
Hellwarth, A. R., electric system, Detroit Edison Company, Detroit, Mich.
Hill, A. W., design engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Horelick, S., president, Pennsylvania Transformer Company, Pittsburgh, Pa.
Hough, W. R., engineer in charge of a-c motor design, Reliance Electric and Engineering Company, Cleveland, Ohio.
Hummel, R. C., technical adviser, West Coast Telephone Company, Everett, Wash.
Jochem, T. B., experimental engineer, Cutler-Hammer, Inc., Milwaukee, Wis.
John, K. W., electrical engineer, United States Rubber Company, Detroit, Mich.
Lallier, W. C., transmission engineer, Wisconsin Telephone Company, Milwaukee, Wis.
Lockwood, L. E., assistant to division operating superintendent, Public Service Company, Evanston, Ill.
Marsh, H. H., assistant general superintendent Duquesne Light Company, Pittsburgh, Pa.
McClure, E. L., assistant system engineer, Wisconsin Electric Power Company, Milwaukee, Wis.
Miner, E. E., construction electrical engineer, The Glenn L. Martin Company, Baltimore, Md.
Parker, C. N., engineer, The Nevada–California Electric Corporation, Riverside, Calif.
Pell, Eric, electrical engineer, Cutler-Hammer, Inc., Milwaukee, Wis.
Rawlins, H. L., section engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Robinson, T. A., electrical engineer, United States Smelting Refining and Mining Co., Salt Lake City, Utah.
Roby, F. H., welding engineer, Square D Company, Milwaukee, Wis.
Roush, C. G., manager, Westinghouse Electric and Manufacturing Company, Kansas City, Mo.
Salton, H. D., development engineer, Pennsylvania Transformer Company, Pittsburgh, Pa.
Saxe, John, manager, electric utility companies in Costa Rica, Costa Rica.
Sessions, R. C., partner, Sessions and Sessions, Cleveland, Ohio.
Stetler, F. E., district foreign wire relations supervisor, Wisconsin Telephone Company, Milwaukee, Wis.
Sullivan, R. J., electrical engineer, Commonwealth and Southern Corporation, Jackson, Mich.
Witzel, E. R., electrical engineer, Kohler Company, Kohler, Wis.

35 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before June 30, 1941, or August 31, 1941 if the applicant resides outside of the United States or Canada.

United States and Canada

1. North Eastern

Blomstedt, H. D., Narragansett Electric Company, Providence, R. I.
Campbell, H. E., General Electric Company, Schenectady, N. Y.
Fjeld, J. M., New York Power and Light Corporation, Albany, New York.
Franklin, I. L., General Electric Company, Schenectady, N. Y.
Gronbeck, J. W., Narragansett Electric Company, Providence, R. I.
Haner, L. P., E. I. du Pont de Nemours and Company, Incorporated, Station B, Buffalo, N. Y.
Hogg, J. E., General Electric Company, Schenectady, N. Y.
Hoyt, G. A., General Electric Company, Schenectady, New York.
Kidder, J. W. (Member re-election), New England Telephone and Telegraph Company, Boston, Mass.
Merkling, W. G., Central New York Power Corporation, Oswego, N. Y.
Schaefer, F. J., Wm. H. J. Hooper, Boston, Mass.
Shappee, F. C., Central New York Power Corporation, Minetto, N. Y.
Smith, W. M., F. W. Sickles Company, Chicopee, Massachusetts.

2. Middle Eastern

Ali, N. J., 125 Hough Street, Morgantown, W. Va.
Bergeron, P., Cleveland Electric Illuminating Company, Cleveland, Ohio.
Boisseau, A. C., General Electric Company, Philadelphia, Pa.
Byrne, J. F., Bell Telephone Company of Pennsylvania, Pittsburgh, Pa.
Chase, M., Rural Electrification Administration, Washington, D. C.
Delahooke, H. R., North Electric Manufacturing Company, Galion, Ohio.
Finn, E. B., Insulation Manufacturers Corporation, Cleveland, Ohio.
Gieser, L. B., Potomac Electric Power Company, Washington, D. C.
Gillenwater, G. A., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Green, C. R., Austin Company, Cleveland, Ohio.
Hamilton, H. L., I-T-E Circuit Breaker Company, Philadelphia, Pa.
Havercamp, W. B., WGAL, Incorporated, Lancaster, Pa.
Heiges, G. E. (Member), Heiges McCullough Company, Incorporated, Sharon, Pa.
Hufford, D. W. (Member), War Department. Corps of Engineers, U. S. Engineer Office, Huntington, W. Va.
Jensen, O., I-T-E Circuit Breaker Company, Philadelphia, Pa.
Kerr, M. P. (Member), Wheeling Electric Company, Wheeling, West Va.
Kuhn, H. R., Trumbull Electric Manufacturing Company, Norwood, Ohio.
Link, E. O., North Electric Manufacturing Company, Galion, Ohio.
Ludwig, C. H., Potomac Electric Power Company, Washington, D. C.
Mack, R., Cleveland Electric Illuminating Company, Cleveland, Ohio.
Marsh, C. O., Jr., National Bureau of Standards, Washington, D. C.
McLain, I. C. (Member), Rural Electrification Administration, Washington, D. C.
Mikina, S. J. (Member), Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Moldenhauer, E. W., Rural Electrification Administration, Washington, D. C.
Oeltjen, W. O., Rural Electrification Administration, Washington, D. C.
Polson, J. T., Cleveland Electric Illuminating Company, Cleveland, Ohio.
Prasek, C. J., Cleveland Electric Illuminating Company, Ashtabula, Ohio.
Shangraw, R. L. (Member), Rural Electrification Administration, Washington, D. C.
Simpson, W. E., Potomac Electric Power Company, Washington, D. C.
Sparing, W. H., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Talley, D. (Member), c/o Chief Signal Officer, Munitions Bldg., Washington, D. C.
Vergilio, J. L., 504 Erie Building, Cleveland, Ohio.
Vlach, C. J., Cleveland Electric Illuminating Company, Cleveland, Ohio.
Whalin, C. V., Jr., Potomac Electric Power Company, Washington, D. C.
Wildman, J. R., Hickok Electrical Instrument Company, Cleveland, Ohio.
Wilent, G. W., Atlantic Refining Company, Philadelphia, Pa.
Woods, T. B., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

3. New York City

Ellis, W. F., Gibbs and Cox, Incorporated, New York, N. Y.
Engel, G. C., General Time Instruments Corporation, New York, N. Y.
Francis, W. R., Western Union Telegraph Company, New York, New York.
Knapp, M. H., Simplex Wire and Cable Company, New York, N. Y.
Lake, F. J., Consolidated Edison Company of New York Incorporated, New York, N. Y.
Lawrence, J. G. (Member), Caribbean Architect-Engineer, New York, N. Y.
O'Meara, T. J., Manhattan College, New York, N. Y.
Seely, T., Public Service Electric and Gas Company, Newark, N. J.
Tyrner, J. M., Wilson Welder and Metals Company, Incorporated, New York, N. Y.
Zinn, M. K. (Member), Bell Telephone Laboratories, Incorporated, New York, N. Y.

4. Southern

Amerine, H. G., Jr., Tennessee Valley Authority, Knoxville, Tennessee.
Boysworth, J. T., Carolina Aluminum Company, Badin, N. C.
Cecil, H. G. (Member), 505 Cumberland Street, Bristol, Va.
Cooper, W. R., Tennessee Valley Authority, Chattanooga, Tenn.
Fort, W. G. S., United States Army, 62nd Signal Battalion, Fort McPherson, Ga.
Johnson, W. M., Florida Power and Light Company, Miami, Florida.
Owens, J. R., Memphis Light, Gas and Water Division, Memphis, Tenn.
Sigmon, R. M., Jr., Southern Bell Telephone and Telegraph Company, Columbia, S. C.
Smith, C. D. (Member), South Carolina Power Company, Charleston, S. C.
Watkins, W. W. (Member), United States Rubber Company, Hogansville, Ga.

5. Great Lakes

Anger, E. G., Square D Company, Milwaukee, Wisconsin.
Baring, J. W. (Member), Commonwealth Edison Company, Chicago, Ill.
Barnum, W. L., Watervliet Paper Company, Watervliet, Michigan.
Callstrom, B. M., Jr., Southwestern Illinois Coal Corporation, Steelville, Illinois.
Carlson, A. E., Dumore Manufacturing Company Racine, Wisconsin.
Davis, R. S., Bull Dog Electric Products Company, Detroit, Michigan.
Hornbacker, G. B., Central Illinois Light Company, Peoria, Ill.
Jensen, H. A., Nash Kelvinator Corporation, Kenosha, Wisconsin.
Knoff, H. C., Public Lighting Commission, Detroit, Michigan.
La France, P., North Plant, Michigan Alkali Company, Wyandotte, Michigan.
Lynn, R. G., American Hoist and Derrick Company, St. Paul, Minn.
Phelan, J., Indiana and Michigan Electric Company, South Bend, Indiana.
Road, R. A., Duncan Electric Manufacturing Company, Lafayette, Indiana.
Schofield, L. B., Commonwealth Edison Company, Chicago, Ill.
Sherman, V. W. (Member), Chrysler Corporation, Highland Park, Michigan.

6. North Central

Forsman, E. H., Continental Air Lines, Incorporated, Denver, Colorado.
Shaffer, R. E., Montgomery Ward Company, Denver, Colorado.

7. South West

Crail, R., Wichita High School East, Wichita, Kansas.
Lichtenfels, I. W., General Electric Company, St. Louis, Mo.

8. Pacific

Bridgwater, M. M., Arizona Power Corporation, Prescott, Arizona.
Curry, N., 1615 E. First Street, Long Beach, California.
Williams, M. D., General Electric Company, Oakland, California.

9. North West

Corfield, R. J. (Member re-election), Utah Copper Company, Garfield, Utah.
Hoffman, W. L. (Member re-election), Puget Sound Power and Light Company, Seattle, Washington.
Guirkin, L. C., Bonneville Power Administration, Portland, Oregon.
Schulz, G. R., 1233 N. W. 12th Avenue, Portland, Oregon.
Searles, P. D., Oregon Institute of Technology, Portland, Oregon.
Trippett, B. H., Big Lakes Box Company, Klamath Falls, Oregon.

10. Canada

Jones, A. R. (Member), Canadian General Electric Company, Peterborough, Ont., Canada.
McKie, W. M., Canadian General Electric Company, Limited, Peterborough, Ont., Canada.
Rogers, C. L., Hydro Electric Power Commission, Toronto, Ont., Canada.

Total, United States and Canada, 101

Elsewhere

Dessart, J. E., Tongshan Mine, c/o The Kailan Mining Administration, Tongshan, North China.
Gerstmann, B., Bayley and Grimster, Carlton, Melbourne N3, Australia.
Pfeifer, H. P. (Member), Nottebohm Trading Company, Apartado 193, San Salvador, El Salvador, C. A.
Stokvis, L. G. (Member), Compagnie generale d'Electricite, 54 Rue de la Boetie, Paris, France.
Woodward, A. G. V., New Zealand Military Forces, Trentham, New Zealand.

Total, elsewhere, 5.

Recent Section Meetings

Section	Date	Speaker	Topic and Activity	Attendance
Akron	4/ 8/41	W. E. Haskell, N. Y. Herald Tribune	War News and Censorship; motion pictures	103
Central Indiana	4/25/41	N. C. Pearcy, Pub. Utilities Engg. & Serv. Co.	Electricity in the Steel Industry; motion pictures	75
Chicago	2/ 6/41	D. C. Prince, G.E. Co.	Trends in Engineering	150
		R. W. Sorensen, pres., AIEE	Talk	
		H. H. Heuline, nat. sec., AIEE	Talk	
	2/13/41	H. M. Richardson, G.E. Co.	Plastics, Particularly for Insulating; power group meeting	103
	2/27/41	T. O. Millard, G.E. Co.; E. J. Novak, cons. engr.; J. F. Calvert, Northwestern Tech. Inst.	Low Voltage Network Distribution Systems for Industrial Plants and Buildings; industrial group meeting	116
	3/13/41	L. R. Potadle, A.T.&T. Co.	Stevens Point-Minneapolis Cable; joint with Western Soc of Engrs.	217
	4/ 3/41	I. T. Faucett, General Cable Corp	Wire and Cable Developments; election of officers; joint with WSE	113
	4/10/41	Major C. W. Leihy	Aspects of the National Power Pool, Defensively and Afterwards; luncheon meeting	130
	4/24/41	R. M. Schaffer, F. E. Andrews, Hatch, A. F. Hibbeler, and Mr. Sagendorf	Round table discussion of distribution problems	90
Cleveland	4/17/41	F. R. Mautz, Western Reserve Univ.	Applications of Electricity to Medicine	82
		J. D. Andrew, student	The Right Angular Hyperbolic Spiral—A Criterion for Art	
		P. R. Kendall, student	Special Applications of Radio Equipment Joint with Case School Branch	
Columbus	2/12/41	E. G. Romeiser, Illinois Elec. Porcelain Co.	Porcelain for Insulators; joint with Ohio State Univ. Branch	25
	2/18/41	Homer Dudley, Bell Tel. Labs.	The Vocoder, or Remaking Speech Electrically	65
	3/13/41	W. R. Gilsdorf, Spaulding Fibre Co.	Manufacture of Laminated Phenolic Sheets, Rods, and Tubes	17
	3/26/41	F. M. McKay, Columbus & So. Ohio Elec. Co.	Fundamentals of Rate Making; joint with Ohio Univ. Branch	46
	4/10/41	E. R. Raper, Springfield City Hospital Plant	Equipment of the Springfield Hospital	24
Connecticut	4/22/41	F. Cowan, A.T.&T. Co.	Sun Spots and Telephone Service; joint with New Haven Astron. Soc.	92
Denver	4/18/41	J. M. Cage, Univ. of Colorado	Problems in Vacuum Tube Development	130
		R. W. Sorensen, pres. AIEE	Brief talk	
		A. L. Turner, vice-pres., North Cent. Dist.	Brief talk	
East Tennessee	4/15/41	J. E. Housley, Aluminum Co. of America	Power Dispatching at the Alcoa Aluminum Reduction Works; dinner	65
Fort Wayne	2/18/41	C. M. Summers, G.E. Co.	High Potential Testing Equipment for Quantity Production	30
		F. J. Baker, Home Tel. & Tel. Co.	Trends in Communication Systems	
	3/13/41	W. L. Everitt, Ohio State Univ.	Fundamental Principles of Frequency Modulation	160
	4/21/41	R. W. Sorensen, pres., AIEE	Engineering Horizons, Limited	80
Houston	4/ 9/41	L. K. Davis and B. W. Pike, students	Localized Annealing of Rock Bit Bodies	68
		J. B. Parchman, student	A Privacy System Using Frequency Translation	
		R. S. Hoff, student	A High-Impedance Vacuum-Tube Wattmeter	
		O. M. Martin, student	Mathematical Analysis of Nonlinear Circuits Joint with Rice Inst. and Texas A.&M. Branches	
Louisville	4/25/41	F. R. Ellwanger, student	Testing of transformers using the cathode-ray oscillograph; joint with Univ. of Louisville Branch	40
Lynn	10/22/40	B. Adams	A Program of Super-Magic	1,000
	11/12/40	Commander L. C. Stevens, U.S.N.	Development in Naval and Aircraft Equipment Shown by the War	900
	12/10/40	Major D. Sears, Universal newsreel cameraman	Get That Picture	900
	12/17/40	F. B. Silsbee	Electrical Work of the National Bureau of Standards	400
	1/ 7/41		The Story of the Coast Guard; motion pictures	600
	1/28/41	Ruth Bryan Owen	This Business of Diplomacy	1,000
	2/11/41		Illumination	1,000
	3/11/41		Safety Around Electrical Machinery	500
	3/25/41	Capt J Craig	The Philippines Today	1,000
Madison	4/17/41	H. L. Rusch, A. C. Nielsen Co.	Measuring Listening Habits of the American Radio Audience	39
Maryland	4/21/41		Prize paper contest	74
		K. J. Affanasiev	Properties of Magnetic Materials (first prize)	
		H. J. Shafer	Development of Magnetic Theory (second prize)	
		J. A. Harber	A Voltage Regulator for Synchronous Machines (third prize)	
Memphis	4/15/41	Allen Pettee, General Cable Corp	Recent Development in Wire & Cable Construction	22
Michigan	4/15/41	L. A. Hawkins, G.E. Co.	Research in World War; election of officers	175
Minnesota	4/22/41	W. Weden, student	Frequency Modulation	60
		K. Carlson and John Storm, students	Glass-Fiber Insulation	
		M. Haugen, student	Oscillations Due to Loudspeaker-Microphone Feedback	
		T. Hedman, student	Black Light Joint with Univ. of Minn. Branch	
	4/28/41	J. W. Butler, G.E. Co.	Application of Series Capacitors in All Types of Circuits	44
Nebraska	12/ 4/40	E. E. Chilberg, Cent. Nebr. Pub. Power & Irrigation Dist.	Mechanical and Electrical Design of the Transmission Lines	16
N. Mex.–W. Texas	4/ 2/41	R. W. Sorensen, pres., AIEE	Engineering Horizons, Limited; election of officers	53
New Orleans	3/28/41	P. G. Whitmore, Ebasco Services, Inc.	Electric Distribution Practices	101
Niagara Frontier	4/17/41	H. M. Cushing, Buff., Niag. & East. Power Corp.	Oswego Steam Station	58
North Texas	4/21/41	Major E. W. Porter, Air Corps	The Use of Electricity in Modern Airplanes	84
Philadelphia		H. N. Ekvall, Phila. Elec. Co.	Minimum Insulation Level for Lightning Protection of Medium-Voltage Lines	72
		E. W. Boehne, G.E. Co.	Traveling Waves on Very Short Lines Election of officers	
Pittsburgh	4/ 8/41	C. S. Barrett, Carnegie Inst. of Tech.	X-Rays in Industry; election of officers; joint with elec. sec. ESWP	170
	4/22/41	G. B. Dodds and W. E. Marter, Duquesne Light Co.	Protective Relays for Power Systems and Elec. Equipment; joint meeting with elec. sec. of ESWP	126
Pittsfield	11/ 5/40	Carl Robinson	Southeastern Alaska; dinner	975
	11/26/40	K. K. Paluev, G.E. Co.	Creative Imagination, How to Train and Use It; colloquium series	75
	12/ 3/41	J. T. Flynn, writer	The Influence of the Election and the War on Business; dinner	1,010
	12/10/40	M. F. Beavers	Presentation of paper, "Effect of Load Factor on Operation of Power Transformers by Temperature," by V. M. Montsinger	20
		T. E. Palmer	Presentation of paper, "Lightning Currents in Arresters at Stations," by I. W. Gross and W. A. McMorris; colloquium series	
	1/ 7/41	Richard W. Rowan	Secret Agents Against America	1,025
	1/14/41	S. M. Humphrey, Taylor-Winfield Corp.	New Developments in Resistance Welding	58
	2/ 4/41	R. D. Evans, MIT	How Atoms Affect Your Life	960
	2/11/41	P. H. Light, G.E. Co.	Dynamic Overvoltages on Power Systems	15
	3/ 4/41	Howard Higgins	Among the Spirits	1,000
	3/25/41		Four papers presented in competition with four from Schenectady Section; competition won by Pittsfield	175
	4/ 6/41	Fulton Lewis, Jr., commentator	What's Happening in Washington	1,050
Portland	12/10/40	H. P. Beckendorf, Pacific Tel. & Tel. Co.	Community Dial Telephone Exchanges	45
	1/30/41	A. Bailey, A.T.&T. Co.	Coastal Harbor Radio Stations of the Bell System; joint with IRE	95
	3/31/41	W. C. Smith, G.E. Co.	Transformer design and operation	40
	4/16/41		Annual prize papers meeting	70

Recent Section Meetings (continued)

Section	Date	Speaker	Topic and Activity	Attendance
		H. E. Bixby and G. H. Bliesener	Use of Electrical Energy to Heat Rural and Urban Dwellings	
		C. B. Carpenter and U. H. Messenger	A Rectifier With Constant Current Output	
		W. E. Enns	A-C Network Analysis Using Resistance Networks (first prize)	
		O. W. Hurd	Automatic Tie-Line Load Control	
		R. E. McCoy	Division of Load Among a Group of Generators (second prize)	
	4/22/41	R. J. Collins, Pacific Tel. & Tel. Co.	Forecasting	29
Rochester	10/10/40	F. H. Roby, Square D Co.	Precision Timing as Applied to Welding and Industrial Control	78
	10/24/40		Fall party	85
	11/ 7/40	B. O'Brian, Univ. of Rochester	Measurement of Sun's Variability by Telemetering Balloons	60
	11/26/40		Round table discussion of radio progress in 1940	35
	12/ 5/40	C. A. Clark, International Tel. Devel. Corp.	IT&T Selenium Rectifiers	55
	1/ 9/41	G. V. Kullgren, G.E. Co.	Application Engineering Problems	92
	1/16/41		Annual bowling party	45
	2/ 6/41	C. Tuttle, Eastman Kodak Co.	Applications of Photoelectric Photometry in Industry	110
	2/19/41		Round table discussion of new requirements of the Nat. Elec. Code	50
	3/ 6/41	F. S. Goucher, Bell Tel. Labs. Inc.	The Microphone and Research	276
	4/ 3/41	E. M. Bouton, Westinghouse Elec. Elevator Co.	Vertical Transportation	56
St. Louis	4/16/41	A. L. Hughes, Washington Univ.	The Cyclatron	61
San Francisco	3/28/41	H. E. Becker, W.E.&M. Co.	Design, Construction, Application, and Operation of Ignitrons	110
	4/11/41	F. S. Benson, Pacific Gas & Elec. Co.	Electrical Features of Avon Steam Plant; dinner	70
	4/25/41	J. G. Stephenson, student	Hot-Cathode Oscillograph for Recording High Impulse Voltages	80
		W. R. Morton, student	Control of a Shunt Motor by Use of Permatrons	
		J. R. Burch, student	Electric Fencing	
			Joint with Univ. of Santa Clara and Stanford Univ. Branches	
Saskatchewan	2/13/41		Election of officers	5
	3/ 7/41		Executive committee meeting	4
	4/ 7/41		Executive committee meeting	6
Seattle	3/25/41	A. D. Moir, Bunker Hill Smelter Staff	17 Years Engineering in Europe; joint of four founder societies	170
	4/14/41	D. Gjesdahl, student	Radiant Heating Application to Homes	56
		H. J. Winsor, student	Survey of Naval Marine Propulsion	
			Joint meeting with Univ. of Wash. Branch	
Sharon	4/11/41	A. L. Draper, Buhl Planetarium	The Pageant of Easter	125
South Bend	4/29/41	T. W. Dugdale, Ind. & Mich. Elec. Co.	Carrier Current Relays and High-Speed Reclosing Breakers	52
Spokane	4/11/41	A. LeRoy Taylor, vice-pres., North West Dist.	Engineering Education	27
Syracuse	4/17/41	Wm. Bailey, Cornell-Dubilier Elec. Corp.	Application of Capacitors to Industrial and Power Circuits	115
Toledo	4/22/41	R. W. Sorensen, pres., AIEE	Engineering Horizons, Limited; dinner	50
Toronto	4/ 4/41	V. G. Smith, Univ. of Toronto	The Use of Matrices in Communication; illustrated	84
	4/18/41	C. A. Powel, W.E.&M. Co.	Electricity in the National Defense	275
	4/25/41	J. Satterly, Univ. of Toronto	Liquid Air, illustrated; election of officers	199
Washington	4/ 8/41	E. D. Merrill, Capital Transit Co.	Financing Urban Transit	100
		C. A. Robinson, Chesa. & Potomac Tel.Co.	Some Problems of Management Under Present Day Conditions	
		M. L. Sperry, Washington Gas Light Co.	Washington Gas Light Company and National Defense	
		A. G. Neal, Potomac Elec. Pwr. Co.	Operation Under the Washington Sliding Scale Arrangement	
			Meeting in honor of 34 past chairmen	
	4/19/41		Inspection trip through Bethlehem Steel Co.	120
	4/22/41	H. H. Henline, nat. sec., AIEE	Is the Institute Fulfilling Its Obligations to the Engineer; junior technical session	28
	4/24/41	T. J. MacKavanagh, Catholic Univ.	Is the Institute Fulfilling Its Obligations to the Engineer; junior technical session	20
	4/29/41	F. M. Defandorf, National Bureau of Standards	Is the Institute Fulfilling Its Obligations to the Engineer; junior technical session	15
West Virginia	4/16/41	W. E. Vellines, Jr., C.&P. Tel. Co.	Improved Instrumentalities in Intercity Telephone Plant Design	32
Worcester	4/25/41	R. W. Sorensen, pres., AIEE	Engineering Horizons, Limited; dinner	35

Recent Branch Meetings

Branch	Date	Speaker	Topic and Activity	Attendance
Arizona, Univ. of	11/26/40	D. Carter, student	Differential Equations	9
	12/ 3/40	J. C. Clark, counselor	The Importance of Temperamental Characteristics	9
	12/10/40		Business meeting	8
	12/17/40		Open house	32
	1/ 7/41	J. C. Clark, counselor	Getting a Job	9
	1/14/41	J. C. Clark, counselor	Getting a Job (concluded)	7
	2/ 4/41	R. Bookman, student	A Practical Problem in Communication	6
	2/11/41	R. Bookman, student	A Practical Problem in Communication (concluded)	6
	3/ 4/41	G. Floyd, student	Mercury Arc Rectifiers	6
	3/11/41	S. Goldman, student	The Characteristics of Transformer Insulating Materials	6
	3/25/41		Business meeting	6
	4/ 1/41	G. Floyd, student	Station Circuits	5
		R. Bookman, student	Prime Movers	
Arkansas, Univ. of	4/16/41	C. Pittman, student	Mercury Arc Rectifiers	20
		W. Dortch, student	Application of Seismographs	
		L. Shackelford, student	Corona Causes and Prevention	
	4/23/41		Election of officers	15
Brooklyn Poly. Inst. (D.)	3/ 4/41	A. Anderson, Underwriters Labs.	The National Electrical Safety Code	35
	3/11/41	S. Frangoulis, student	The History of Television	35
	3/21/41		Inspection trip through Underwriters Labs.	40
	4/ 1/41	A. Dolan, student	The Design and Construction of a Vacuum-Tube Voltmeter	40
	4/ 9/41	P. Thomas, W.E.&M. Co.	Demonstration	300
	4/24/41		Annual convention at Rutgers Univ., New Brunswick, N. J.	45
Brooklyn, Poly. Inst. (E.)	3/17/41	Mr. Krowl, N.Y.C. Tunnel Authority	Design and layout of the lighting and signal equipment in the Queens-Midtown Tunnel	25
	4/21/41	Robin Beach	Experiences in connection with several court cases	16
Calif. Inst. of Tech.	3/ 7/41		Inspection trip through Paramount sound studios	42
	3/14/41		Inspection trip through Columbia recording studios	10
	4/ 2/41		Inspection trip to the Southern Calif. Edison Co. test dept.	35

Recent Branch Meetings (continued)

Branch	Date	Speaker	Topic and Activity	Attendance
	4/ 7/41	C. B. Stadum, student	The Behavior of Insulators in Hydrogen	
		R. E. Kingsmill, student	The Shielding Effects of Transmission Lines	
Calif., Univ. of	4/ 4/41		Joint with Los Angeles Section, and Univ. of So. Calif. Branch; Inspection trip through Alameda cross-bar exchange	10
	4/14/41		Executive committee meeting	10
	4/14/41	J. Stephenson, student	Trip through the cross-bar telephone exchange	34
		R. C. Balsley, student	Low Voltage Short-Circuits on Distribution Systems	
		J. Burch, student	Electric Fencing	
Carnegie Inst. of Tech.	9/27/40	G. W. Murdock, student	Carbon	50
	10/ 4/40	J. Jenkins, student	Electronic Musical Instruments	50
	10/11/40	J. Darnall, student	Rural Electrifications	50
	10/18/40	G. Klotzbaught, student	Transient Phenomena	50
	10/25/40	G. Wheeler, student	Unit Power Plants	50
	11/ 1/40	Wm. Preece, student	Aeronautical Instruments	50
	11/ 8/40	G. B. Wilson, student	Plastics and Their Application in the Electrical Industry	50
	11/14/40	W. A. Needs, student	Electric Furnaces in Steel Production	50
	11/22/40	R. W. Gilliland, student	The Ionosphere	50
	12/ 6/40	M. L. Levy, student	Gem Cutting	50
	12/13/40	R. Herpick, student	The Story of the Akron	50
	1/10/41	A. Helfer, student	Phonograph Recording	50
	2/ 7/41	L. Drugmong and G. McElwee, students	Frequency Modulation	50
	2/14/41	H. Cooper, student	Battleship Power Plants	50
	2/21/41	C. T. Sinclair, vice-pres., Dist. 2	Advice to the Embryo Engineer	50
	2/28/41	C. A. Powel, W.E.&M. Co.	Application Engineering	50
	3/ 7/41	C. M. Martsolf, Bell Tel. Co.	System Planning Engineering	50
	3/14/41	R. L. Kirk, Duquesne Light Co.	How, Where, and What (Engineering Counsel)	50
	3/21/41	S. Balaban, student	The Incandescent Light	50
	3/28/41	T. B. Whitson, J. J. Biddle Co.	Megger Practice	50
	4/ 4/41	G. T. Fouse, student	Fourth Dimension	50
	4/18/41	F. C. Hesch, student	The Electron Microscope	50
	4/25/41	R. DeStefano, student	Fluorescent Lighting	50
Clarkson Col.	4/23/41	A. R. Powers, counselor	Advantages of the AIEE	15
Colorado State Col.	4/11/41	H. Nuce, student	Electrical Accidents	16
		D. Hendrix, student	MKS System of Units; election of officers	
Colorado, Univ. of	4/ 9/41	W. C. Brown and R. H. West, students	The Amplidyne as a Voltage Regulator; election of officers	35
Columbia University	4/ 7/41		Business meeting	15
	4/24/41		Business meeting	15
	5/ 5/41		Business meeting	15
Conn., Univ. of	2/20/41	E. S. Lee, vice-pres., North East. Dist.	The Prominence of Measurements in Industry; inaugural meeting	159
	2/28/41	H. P. Stone, student	De-Ion Circuit Breakers	22
	3/21/41	J. H. Lampe, dean of engg.	Talk on experiences with power companies; election of officers	24
Cooper Union (E.)	4/11/41	B. Shmulevitz, student	A Survey of Frequency Modulation	25
Cornell Univ.	4/16/41	E. T. B. Gross	Euclid Applied to Circle Diagrams	38
Detroit, Univ. of	1/14/41	T. S. Cawthorne, Weston Elec. Inst. Co.	Design Details of Electrical Instruments	54
	2/26/41		Social meeting	63
	3/12/41	Wm. Dean, senior	Fundamentals of Radio Broadcasting; motion pictures	58
Drexel Inst. of Tech.	4/ 9/41	T. P. Moody, N. Y. Shipbuilding Co.	Problems of Modern Transit Ship Design	55
Duke Univ.	10/ 1/40	W. J. Seeley	AIEE activities	22
	10/15/40	G. Bennett, Durham Public Service Co.	Situations met by a public service engineer	21
	11/ 5/40	C. R. Vail, Duke Univ.	Engineering Experiences at the World's Fair	19
	11/19/40	O. Meier, Jr., counselor	Demonstration of fluorescent lighting circuits	25
	12/10/40	T. S. Shinn, Carolina Power & Light Co.	Engineering Safety	21
	1/ 7/41		Talks on various subjects by faculty members	20
	1/28/41	Members of the Durham Fire Dept.	Demonstrations on safety precautions and first aid treatment	28
	2/28/41		Discussion of engineers' show	25
	3/ 4/41	H. Hart, Duke Univ.	Happiness	28
George Washington Univ.	9/25/40	F. Hermach, student	Electrical Units and Standards	26
	10/ 2/40		Semiannual engineers' mixer	155
	11/ 6/40	H. H. Rogge, W.E.&M. Co.	The Electrical Engineer as a Salesman	39
	12/ 4/40	D. C. Coyle, consulting engr.	Engineering Economics of Capitalism	73
Georgia Sch. of Tech.	4/18/41	K. Weisiger, Southern Bell Tel. & Tel. Co.	The Engineer's Place in National Defense	53
Harvard Univ.	2/20/41	J. P. Newton, student	Analysis of the Capacitor Motor	27
		F. W. White, Jr., student	Spark Discharge in Air at Atmospheric Pressure	
	3/13/41	C. L. Dawes, Harvard Univ.	Alexanderson Thyratron Motor	30
	3/27/41		Motion pictures	20
Illinois Inst. of Tech.	4/ 4/41	Robert Zane, Okonite Corp.	Discussion of wires and cables; motion picture on Okonite products	45
	4/18/41		Election of officers	40
	4/24/41		Annual smoker	85
Illinois, Univ. of	2/19/41	H. L. Oleson, Weston Electric Inst. Co.	Meet a Meter	75
	2/26/41	E. S. Lee, G.E. Co.	The Prominence of Measurements in Industry	90
Iowa State Col.	4/23/41		General discussion	29
Iowa, Univ. of	4/16/41		Motion pictures	40
	4/30/41	E. L. Goss, student	Ultrasonics	33
		F. C. Vernon, student	Construction of Commutators	
		B. Hills, student	Polyphase Currents in Squirrel Cage Motors	
Johns Hopkins Univ.	2/ 7/41	R. Weller, student	Relays and Their Operations	18
		C. Bechtel, student	Velocity Modulation of Electron Discharge	
	2/21/41	I. C. Tillman, student	Geiger Counters	16
		R. Bell, student	Expulsion Gap Protection	
	3/ 7/41	R. D. Case, student	Test Equipment for Transformers	16
		E. Melvin, student	Ultrahigh-Frequency Propagation	
	3/21/41	W. L. Wilkerson, student	Electric Locomotives	17
	4/ 3/41	E. Eager, student	Conowingo Dam	28
	4/11/41		Election of officers	32
Kansas, Univ. of	3/25/41	J. L. Hamilton, vice-pres., South West Dist.	Engineering—Past, Present, and Future	20
	4/ 3/41	R. York, student	Feedback	40
		J. Laidig, student	Commutation Currents	
Kentucky, Univ. of	4/11/41		Discussion of recent inspection trip	50
	4/25/41		Election of officers	30
Lehigh Univ.	12/19/40		Dinner	71
	3/20/41	W. H. Vogelsberg, student	The Hammond Electric Organ	42
	4/17/41	W. H. Formhals, W.E.&M.Co.	Electrical Equipment for Modern Machine Tools	45

Recent Branch Meetings (continued)

Branch	Date	Speaker	Topic and Activity	Attendance
Maine, Univ. of	4/10/41	David Byer, student	Trip to Ford River Rouge Plant and W.E.&M. Co.	8
		Mr. Brown, student	Research laboratory at M.I.T.	
		C. Preble, student	Experiences in summer employment	
	4/22/41		Election of Branch chairman	16
	4/28/41	R. W. Sorensen, pres., AIEE	Engineering Horizons, Limited	222
Mich. Col. of M.&T.	4/15/41		Social meeting	40
Michigan State Col.	4/ 9/41	Mr. Wills, U. S. Weather Bureau	The Weather	26
	4/22/41	C. E. Fishbeck, Detroit Edison Co.	System Operation	32
Michigan, Univ. of	4/22/41	O. S. Duffendak, Univ. of Mich.	The Electron Microscope	43
Minnesota, Univ. of	3/ 5/41	Ming-China Swen, student	Engineering and Living Conditions in China; motion pictures	32
Missouri Sch. of M.&M.	3/19/41	B. Sexton, student	G.E. developments of the past year	17
		M. Block, student	Nomographs for Electrical Calculations	
		L. Kueker, student	Electron Microscope	
	4/ 1/41		Motion pictures	52
Missouri, Univ. of	10/29/40	G. Green, student	Fluorescent Lighting	36
		P. Smith, student	Lighting, the Incandescent Lamp	
	2/18/41	L. A. Nickell, Columbia Ice Co.	Setting Up of Small Power Plants; Operation of an Ice Plant	23
	4/ 1/41		Discussion of future activities	25
Montana State Col.	4/ 8/41	Mr. Williams, Montana Power Co.	Watt-Hour Meters	25
Nebraska, Univ. of	4/16/41	Mr. Pappas, student	The New KFOR Transmitter	39
Nevada, Univ. of	2/25/41	L. N. Roberts, Pacific Tel. & Tel. Co.	New Requirements in Industrial Leadership	19
	3/ 4/41		Preparations for Engineers' Day	28
	4/22/41	R. L. Shipp, student	The Hysteresograph	17
	4/29/41	L. L. Stoffel, Ohio Carbon Co.	Carbon Manufacturing; election of officers	19
New Hampshire, Univ. of	4/24/41		Election of officers	19
New Mexico State Col.	4/17/41		Election of officers	11
New Mexico, Univ. of	4/17/41		Election of officers	14
New York Univ. (E.)	4/ 2/41	I. Ritter, N.Y.U.	Exterior Ballistics	23
	4/30/41		Business meeting	17
N. C. State Col.	4/ 1/41		Discussion of plans for Engineers' Fair	59
	4/15/41	W. H. Blue, student	Description of the District conf. on student activities	37
	4/22/41		Election of officers	46
N. Dak. State Col.	4/ 3/41		Discussion of future papers	15
	4/ 8/41		Discussion of papers to be presented at student convention; election of officers	16
N. Dak., Univ. of	4/ 8/41	R. E. Smith and K. Smith, students	Ultraviolet Rays	16
		F. Olson and H. Hanson, students	The Coloratron	
	4/23/41		General discussion	14
Ohio State Univ.	2/ 6/41	J. T. Newman, student	Electricity Up to the Time of Franklin	38
	2/12/41	E. G. Romeiser, Illinois Elec. Porcelain Co.	Porcelain the Paragon of Insulators	70
	2/20/41	J. Cumming, student	Duties of a Substation Crew Man	28
	3/ 3/41	F. O. Wisman, student	Synthetic Symmetry in Mutual Inductance Balance	29
	3/7–8/41		Inspection trips and technical sessions; joint with Univ. of Cincinnati and Ohio Northern Univ. Branches	39
Ohio Univ.	10/23/40	P. Ford, student	Who Are the Engineers	12
	11/20/40		Business meeting	15
	3/ 5/41		Business meeting	17
	3/26/41	F. M. McKay, Southern Ohio Elec. Co.	Fundamentals of Rate Making; joint with Columbus Section	30
	4/30/41		Election of officers	10
Oklahoma, Univ. of	4/ 3/41	J. Straiton, student	Inverse Feedback of Rectified Radio Frequency; motion pictures	25
Oregon State Col.	2/19/41	W. R. Volheye, Oregon Bureau of Labor	Obligations of employers and workmen under Oregon Safety Code	28
	3/ 6/41	C. J. Hawkes, Electric Storage Battery Co.	Storage Batteries in Industry	56
	4/ 3/41	C. C. White, L. Chaffin, and J. N. Paszkowski, students	Symposium: Desirable Training for the Engineering Profession	28
Pennsylvania State Col.	4/2–9/41		Inspection trip	57
	4/28/41	J. O. Perrine, A.T.&T. Co.	The Artificial Creation of Speech	800
Pennsylvania, Univ. of	4/28/41		Annual student branch convention	185
Pittsburgh, Univ. of	9/26/40	J. V. Heish, student	Types of oil deposits and use of instruments in development work	90
	10/ 3/40		Motion pictures	90
	10/10/40	H. H. Miller, student	The Signal Generator—Its Operation and Applications	89
		J. Dugan, student	Marine Mines in Our Coastal Defense	
	10/17/40	H. A. Brant, student	Current Diversion	89
	10/24/40	R. C. Gorham, counselor	Middle Eastern District meeting	
		W. P. Smith, student	History of Eta Kappa Nu	
	10/31/40		Motion pictures	89
	11/ 7/40	C. W. Drake, W.E.&M. Co.	Outline of various jobs	90
	11/14/40	R. A. Kirkpatrick, Union Pacific Railroad	Boulder Dam	90
	11/21/40	James Rial, student	Function of the Engg. and Mines Committee of Y.M.C.A.	88
		Dr. Farmer, university chaplain	Value of Religion	
	11/21/40	F. N. Blum, student	Pennsylvania Electric Co.	88
		C. O. Beltz, student	The Manufacture of an A-C Motor	
	12/12/40	L. A. Terven, West Penn Pwr. Co.	Growth of Power Utilities	89
	1/ 9/41	E. A. Holbrook, dean of engg.	National Defense Program	89
	1/16/41	L. Barranti, student	Fluorescent Lighting	90
		R. Parker, student	Hydrogen Cooled Generators	
	1/23/41	W. D. Brown, Duquesne Light Co.	Primary System of Duquesne Light and Its Interconnections	90
	2/13/41	J. Unitus, U. S. Secret Service	Know Your Money	89
	2/20/41	Mr. Compton, Duquesne Light Co.	Relay Protective Devices	89
	2/27/41	S. Kovacevic, student	High Speed Photography	90
		J. Quinn, student	Electrical Precipitation Applied to Cleaning Gases	
	3/ 6/41	D. I. Baun, Aluminum Co. of America	Aluminum Company of America's Power Holdings in the U. S.	90
	3/13/41		Annual presentation of Eta Kappa Nu pledges	87
	3/20/41	W. G. Crouch, Prof.	Why We Go to See a Tragedy	87
	3/27/41	J. Barclay Whitson, J. G. Biddle Co.	The Megger Instrument	89
	4/ 3/41	D. Ornitz and A. Lasday, students	The Mass Spectograph	89
	4/17/41	R. Powell, student	Concrete Research	
	4/24/41	John McWade, student	Frequency Modulation	81
Pratt Inst.	3/29/41		Inspection trip through X-Ray Division of W.E.&M. Co.	7
	4/ 3/41	W. Beagan, student	Sperry Rail Testers	35
		H. Pinkham, student	Measurement of Light	
		G. E. Gilmore, student	Electrical Power Requirements for National Defense	
	4/18/41	P. Thomas, W.E.&M. Co.	Demonstration	91
Purdue Univ.	4/16/41	H. P. St. Clair, American Gas & Elec. Corp.	The theory and characteristics of multiwinding transformers	50

Recent Branch Meetings (continued)

Branch	Date	Speaker	Topic and Activity	Attendance
Rice Inst.	3/13/41	J. L. Hamilton, vice-pres., South West Dist.	Advantages of AIEE membership; joint with Texas A.&M. Col. Branch	58
	4/ 9/41	L. K. Davis and B. W. Pike, students	Localized Annealing of Rock Bit Bodies	68
		R. S. Hoff, student	A High Impedance Vacuum Tube Wattmeter	
		J. Parchman, student	A Privacy System Using Frequency Translation	
		O. M. Martin, student	Mathematical Analysis of Nonlinear Circuits	
			Joint with Texas A.&M. Branch and Houston Section	
Rutgers Univ.	1/15/41	R. Kennedy, student	The Future of Engineering at Rutgers	30
		S. Mason, student	The Mechanical Integraph and Planimeter	
		M. Scherb, student	Frequency Modulation	
	2/27/41	H. Johnson, Rutgers Univ	Illustrated talk on trip to Greenland	31
Santa Clara, Univ. of	1/14/41	W. Morton, student	Processes involved in reducing timber to lumber	14
	1/28/41	J. Ganahl, student	Construction of the Prado Dam	15
	2/26/41	Mr. Ryan, student	Safety in the Electrical Testing Laboratory	21
	3/11/41	J. Susoeff, student	Electricity in Medicine	11
		F. M. Howe, student	Functions of the Line Crew of the P.G.&E. Co.	
	3/28/41	J. Dorn, student	Applications in Lighting	10
	4/23/41	W. Morton, student	Speed Control of Shunt Motors; election of officers	13
S. Dak. State Col.	10/ 2/40		Motion pictures	22
	10/16/40		Demonstration on fluorescent lighting	25
	11/20/40		Discussion on frequency modulation	23
	12/ 4/40		Discussion on frequency modulation	15
	1/ 8/41		Motion pictures	25
	2/ 5/41		Demonstration of electrical method of transposing international code signals into a typewritten message	25
	2/19/41		Discussion on nomography	15
	3/ 5/41		Election of officers	25
	3/18/41		Business meeting	7
	4/ 2/41		Explanation of television methods	27
	4/16/41	H. Johnson and K. Hammer, students	Papers	12
	4/18–19/41	R. Barthle and V. Winters, students	Amateur Television	8
	4/30/41		Discussion	12
S. Dak. State Sch. of Mines	4/ 3/41		Discussion of future plans; election of Branch chairman	12
So. Calif. Univ. of	3/27/41		Inspection trip through RCA recording studios	20
	4/ 8/41	Mr. Kingsmill, student	The Shielding Effect of Towers on Transmission Line Conductors	120
		Messrs. Dawson and Stadum, students	The Behavior of Insulators in Hydrogen	
		L. Wilson, student	Power Factor Measurements by Vacuum Tube Voltmeter	
		Mr. Romero, student	New Frontiers in Southern Calif.	
		R. Hedges, student	An Electrical Method for Automatic Musical Transposition	
			Joint with Los Angeles Section and Calif. Inst. of Tech. Branch	
	4/15/41	W. Cline, Don Lee Television Sta. WcXAO	Problems met with in building and operating a television station	25
Stanford Univ.	4/16/41	R. V. Howard, Radio Station KSFO	Theoretical and Practical Aspects of Wave Propagation as Applied to Radio Broadcasting; election of officers	65
	4/26/41		Inspection trip through the P.G.&E. Co.	8
Swarthmore Col.	3/13/41		Election of officers	7
	4/15/41	M. I. Allen, Philadelphia Elec. Co.	Some Aspects of Utility Power Service	26
Tennessee, Univ. of	1/22/41		Motion pictures	16
	2/13/41		Motion pictures	50
Texas A.&M. Col.	3/13/41		Discussion	21
	3/27/41		Motion pictures	43
	4/17/41		Election of chairman	23
Texas Tech. Col.	4/21/41	W. D. Price, Texas-New Mexico Utilities Co.	Automatic Control; election of officers	22
Texas, Univ. of	3/31/41	Mr. Morehouse, Leeds & Northrup Corp.	Control of Load Frequency on Interconnected Power Systems	38
	4/15/41		Election of officers	19
Tufts Col.	4/17/41		Election of officers	29
Tulane Univ.	3/ 7/41	B. Lavitola, student	Placing the Decimal Point in Slide Rule Computations; election of officers	22
	4/10/41		Motion pictures	15
	4/18/41	Messrs. Basnett and DeLerno, students	An Electronic Circuit for Determining Power Angle Oscillations	39
		Messrs. Haley, Herrod, and Lockwood, students	Remote Control by Radio	
			Joint with New Orleans Section	
Union College	4/29/41	Fred Fisch, Bureau of Traffic and City Planning	Traffic Control Equipment; election of officers	50
Utah, Univ. of	2/14/41	R. W. Sorensen, pres., AIEE	Engineering Horizons, Limited	50
	3/12/41	E. Backman	Development of electrical apparatus in the mining industry	38
	3/24/41		Discussion of plans for Engineering Week exhibits	25
	4/24/41		Election of officers	31
Vermont, Univ. of	1/17/41	R. Marshall, student	Research laboratory of the Sprague Specialties Co.	12
	2/ 7/41	E. R. McKee, counselor	Plans for Engineers' Day	29
	3/ 7/41	H. B. Coburn, student	ROTC summer training camp at Fort Devens	14
	4/11/41		Motion pictures	18
	4/18/41		Election of officers; motion pictures	15
	4/25/41	B. P. Brown, student	A New Television Antenna	15
Virginia Poly. Inst.	4/10/41		Annual smoker	71
	4/17/41		General discussion	41
Virginia, Univ. of	9/24/40	L. A. Quarles, counselor	AIEE activities	25
	10/29/40		Discussion of future activities	17
	11/16/40		Inspection trip to Va. Pub. Serv. Co.	14
	1/29/41	P. Peyton, student	The Advantages of Frequency Modulation in Radio	16
	2/19/41	C. Y. Johnson, student	Instrument Landing for Aircraft by Radio	14
Washington State Col.	4/17/41	Capt. Grafton, Military Dept.	Informal talk	26
Washington, Univ. of	3/ 7/41	C. Terrell, Puget Sound Pwr. & Lt. Co.	Notes of an Engineer	57
	4/25/41		Inspection tour of Bremerton Navy Yard	59
Washington Univ.	4/ 7/41		A Resonant Type of Constant Current Regulator	
	4/21/41		Inspection trip through G.E. Lamp Works	17
	4/21/41		Election of officers	26
West Virginia Univ.	4/14/41		Motion pictures	35
Wisconsin, Univ. of	4/17/41	H. Rusch, A. C. Nielsen Co.	Measuring Listening Habits of the American Radio Audience	45
Wyoming, Univ. of	4/ 9/41	S. Phillips, student	Airways Radio Ranges; election of officers	13
	4/22/41		Discussion of future activities	8
	4/28/41		Discussion of Engineers' Open House Display	15

Of Current Interest

Engineers and Selective Service

ALTHOUGH the Selective Service Act provides that no deferment of military service shall be made for occupational groups or groups of individuals in any plant or institution, constructive efforts are being made by Selective Service officials and by many local draft boards to defer from routine military service those men who are necessary in the production of National Defense materials and those students who are preparing themselves for service in defense industries and other activities vital to the national safety. This general subject has been discussed by AIEE President R. W. Sorensen in his messages to the Institute membership published in the March issue (*pages 127–8*), the April issue (*pages 175–7*), and again in this issue (*page 279*). The subject also was discussed by President Harvey N. Davis of Stevens Institute of Technology, Hoboken, N. J., in an address delivered at the AIEE North Eastern District meeting, Rochester, N. Y., May 1, 1941, full text of which is included elsewhere in this issue (*pages 247–50*); and by W. S. Fielding (A'38) in the "Letters to the Editor" columns of this issue.

Studies made by the Bureau of Labor Statistics for the Office of Production Management show that the supply of man power in the following specialized professional fields is "at a dangerously low level":

Chemistry
Engineering
  Civil
  Electrical
  Chemical
  Mining and Metallurgical
  Mechanical

Authorities claim that shortages exist also in other technical fields not yet studied by the Bureau.

SPECIFIC PROVISIONS

Section 5(*e*) of the Selective Service Act specifically authorized the President to provide for the deferment from service and training of those men whose employment in any industry, agriculture, or other endeavors as found by the local board to be necessary to the maintenance of the national health, safety, or interest. Under the authority of this provision the President, in Section XXII of the Regulations, specifically directed local boards to defer all registrants found so to be necessary. In paragraph 352*b* he calls particular attention to the importance of protecting the National Defense program:

"In determining whether a registrant is a 'necessary man,' the local board shall give due consideration to those registrants engaged in any activity which is essential to the national health, safety, or interest in the sense that a serious interruption or delay in such activity is likely to impede the national defense program."

Local boards must give full weight to this provision in dealing with the claims for occupational deferment of necessary men engaged in activities necessary to the National Defense, including those necessary to defense production. A dual responsibility is imposed upon local boards as they must not only select those who are needed by the armed forces, but must also defer those who are necessary in the production of defense materials. They must take fully into consideration the entire National Defense picture in making that selection or deferment.

A "necessary man" is defined in the Selective Service Regulations as follows:

"A registrant shall be considered a 'necessary man' in industry, business, employment, agricultural pursuit, governmental service, or in any other service or endeavor, including training or preparation therefore, only when all of these conditions exist:

(*a*). He is, or but for a seasonal or temporary interruption would be, engaged in such activity.

(*b*). He cannot be replaced satisfactorily because of a shortage of persons with his qualifications or skill in such activity.

(*c*). His removal would cause a material loss of effectiveness in such activity."

One of the most recent efforts to prevent "necessary men" from being drafted into routine military service consisted of a telegram sent by Brigadier General Lewis B. Hershey, Deputy Director of Selective Service, to all Selective Service State Directors, calling attention to the growing need for skilled industrial workers in our rapidly expanding and vitally important defense industries, and pointing out that it is a basic provision of the Selective Training and Service Act of 1940 that it must be so administered "as not to interrupt, delay, or impede the National Defense program."

"Selective Service regulations," General Hershey said, "were written with respect to occupational deferments to guide local boards and to achieve the following three results: (1) to prevent any unnecessary aggravation of existing shortages of necessary workers in defense activities by broad and intelligent understanding of the magnitude of the Nation's program for defense production; (2) to protect the national industrial-training program from unnecessary interruptions by deferment of individuals when evidence shows that they are 'in training or preparation' for an occupation or employment found to be necessary to the maintenance of the national health, safety or interests, and (3) to anticipate possible exhaustion of pools of highly skilled workers not now employed in defense activities but probably necessary in the near future for the expansion of defense production, when such men, 'but for a seasonal or temporary interruption would be engaged in such defense activity.' "

DEFERMENT OF STUDENTS

The proper classification of students and other registrants in training or preparation constitutes one of the major problems of the Selective Service system. It is provided that a registrant may be deferred if he is found by the local board to be a necessary man in any industry, business employment, agricultural pursuit, governmental service, or any other service or endeavor, or in training or preparation therefore, the maintenance of which is necessary to the national health, safety, or interest. Therefore, students may be deferred where the activity for which they are being prepared is one essential to the national health, safety, or interest. The necessity of providing the required replacements for, and additions to, those men deemed by local boards as being engaged in essential activities, should be considered by local boards in making their determination of individual cases. In determining whether or not a student is a "necessary man," the local boards have been instructed to give due consideration to such factors as the length of time which the student has been pursuing the course in question, his relative progress and standing, and his relative chances for employment in the activity for which he is preparing.

As has been emphasized repeatedly, each individual case is considered by the local boards solely on its own merits and available information; in all instances the final decision is up to the local boards. Therefore, it is vitally important that the local boards be given complete information by or directly in behalf of each individual registrant, if "necessary men" are not to continue to be drafted into services where they can contribute less to the national safety. As Doctor Davis and Doctor Sorensen so appropriately have emphasized, it is the *patriotic duty* of every individual to do everything in his power to aid in his placement where his abilities can be utilized to the fullest possible advantage of the manifold and increasingly vital defense program.

Decentralization the Goal in Locating New Defense Plants

Decentralization appears to be the goal toward which the Government is aiming in locating new factories for the manufacture of defense equipment. Factors that will guide the Government in selecting plant sites were discussed in a recent issue of the *United States News;* excerpts from which follow.

"Well along toward completion is the first $2,500,000,000 batch of Government and privately financed plants. Defense preparations call for at least that much additional construction. . . . Many factories designed primarily for defense probably will become lasting parts of the nation's industrial apparatus when the emergency has passed. Aluminum plants in the South and Northwest, Tennessee Valley Authority power expansion, the Houston area's $17,000,000 steel project are samples of undertakings with long-range utility . . . .

"Over the longer run, regional planning to solve unemployment, farm problems, and urban congestion seems likely to receive attention. The next wave of plant expansion is expected to bring out more clearly decentralization ideas now strongly advocated by key defense planners for military reasons and for building up areas of potential industrial strength. The stupendous job of creating a war industry to out-produce Nazi-dominated Europe may help bring the city and farm closer together . . . .

"In terms of geography, the trend points toward acceleration of industrial shifts into the South and West. For strategic reasons alone, the War Department wants plants out of range of air, sea, and land thrusts at exposed coastal areas . . . . Already preliminary steps have been taken for moving plants inland . . . .

"The first rush for speed piled up orders and new plant construction in existing industrial areas. This tended to increase concentration, rather than redistribute industry . . . . The North and East drew most of the plant construction. Of 273 Government-financed projects costing nearly $1,700,000,000, more than a third went to New York, Ohio, Indiana, Michigan, and Pennsylvania. Seaboard shipbuilding and the placing of aircraft and motor factories near automotive centers partly explains the concentration . . . . But some strides have been taken toward sheltering aircraft, motor, and parts factories in the interior. Munitions plants have started the hike across the mountains. Chemical, aluminum, brass, and miscellaneous supply units have been located at inland points in the initial construction program.

"Government has various means of guiding plant migration. It hands out the orders. Then it does the bulk of the financing, directly or indirectly. Hydroelectric developments, on the TVA pattern, exercise the pull of cheap power. Often a request to industrial management is sufficient. Moreover, Washington now holds the purse strings on large housing expenditures, important for building defense production centers.

"When the search for sites gets down to brass tacks, natural advantages demand consideration. The War Department specifies, for instance, that a site for a smokeless powder plant must satisfy these requirements: (1) large space (about 6,000 acres) free of oil, gas, and water lines; (2) nearby raw materials, including cotton linters or wood pulp, nitric acid, coal, water; (3) facilities for disposal of waste materials; (4) transportation; (5) adequate labor supply; (6) electric power . . . .

"With the passing of the opening drive for production speed, long-range factors of economic planning will get more attention. Plant site experts theorize that planning must be directed toward giving the country the best possible balanced economy—between farm and city, region and region—after the emergency has passed. Concretely this means, in site selection: (1) avoiding communities where defense orders already have soaked up the labor supply; (2) shifting production from cities where housing, transportation, and electric power capacity have been strained; (3) favoring communities with the greatest unemployment; (4) directing the movement of industry south and west."

Fire Defense Discussed by NFPA

Fire defense was the keynote of the 45th annual meeting of the National Fire Protection Association held at the Royal York Hotel, Toronto, Ontario, Can., May 12–16. Among the principal topics discussed were the essential measures to safeguard defense production from interruption by fire due to sabotage, bombing, or the many accidental hazards associated with emergency production.

Protection of cities from possible effects of incendiary bombing and the organization and equipment best suited for the fire defense of American and Canadian cities were reviewed in detail. Special fire problems in aviation, parachute fighting of forest fires, civilian defense plans, and other important topics were discussed by prominent speakers.

Signal Corps Reserve Officers Needed

A thorough canvass of all possible sources to fill the reserve-officer shortage in the Signal Corps is now under way by the United States War Department. Some 1,500 to 3,000 reserve officers are needed in addition to the 1,500 now on duty, the important need being for lieutenants and captains.

Since practically all of the reserve officers in the Signal Corps now are on duty, the War Department announced that "the acute shortage must be met by drawing men with the proper qualifications from other branches of the Army." In this expansion program, preference will be given to all graduate electrical engineers and to those who have experience or training in Signal Corps operation.

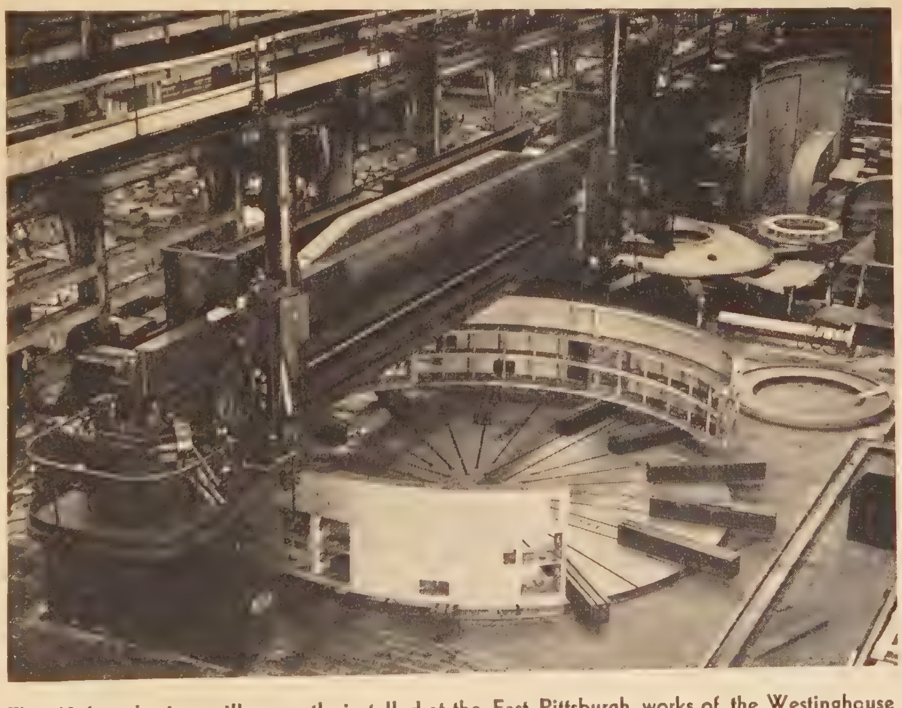
Defense Training Chart

A condensed chart-guide to defense-training opportunities in programs sponsored by Federal agencies has been compiled and issued by the United States Office of Education. The chart-guide, which measures 18 by 23 inches, is entitled "Defense Job Training." It covers 24 training programs including vocational training for persons who have never had a job, advanced training for persons now at work, training of engineers, specialized instruction in radio and at cooks and bakers schools, pilot training (both civil and military), airport attendant preparation, and training for merchant marine ships' officers and crews.

Information which the chart-guide presents to persons interested in a defense job includes: (1) number to be trained or in training in fiscal year 1941; (2) wages in training; (3) fees in training; (4) wages on job; (5) purpose of training; (6) persons eligible; (7) length of courses; (8) where offered; (9) where to apply; and (10) jobs for which training qualifies. Single copies of the chart may be obtained from the Superintendent of Documents, Government Printing Office, Washington, D. C., at five cents each; bulk prices are $2 a hundred, $15 a thousand.

Simplified Stock Sizes of Conductors Proposed

In order to facilitate the national defense program, the adoption of a simplified list of stock sizes of copper conductors has been proposed as a means of reducing unnecessary inventories of copper wire, thus effecting economies and conserving material, ac-



This 40-foot boring mill, recently installed at the East Pittsburgh works of the Westinghouse Electric and Manufacturing Company, is aiding in the construction of large power equipment for the national defense program. This view shows the stator frame of a 30,000-kw water-wheel generator being assembled on the turntable in preparation for machining; for this operation the turntable speed is about 0.34 rpm

cording to an announcement by the National Bureau of Standards, United States Department of Commerce. The proposed simplified list was drafted at a general conference held under the auspices of the Division of Simplified Practice and is now being submitted to the industry, in the form of a Proposed Simplified Practice Recommendation, for consideration and acceptance.

The National Electrical Contractors Association, sponsor of the proposed recommendation, called attention to the fact that appreciable copper tonnages are now tied up in inventories of slow moving sizes, mostly in the upper size range, whose place could be filled more efficiently, from an electrical standpoint, by smaller cables connected in multiple. Therefore, the association suggested the adoption of a simplified list of 19 stock sizes of copper conductors in the range from number 14 (American wire gauge) to 500,000 circular mils, also that sizes larger than 500,000 circular mils be not carried in stock, but should be available only on order.

The general conference, called to consider this suggestion, consisted of representatives of manufacturers, distributors, users (including Governmental agencies) and others interested. After thorough consideration of the relative demand for the various sizes proposed for inclusion in the simplified list, the conferees unanimously decided that the demand for sizes number 5 and number 3 was not sufficient to warrant their retention. With this modification, the suggestions of the sponsoring group were drafted into a recommendation, to become effective for new production for stock, June 1, 1941, subject to approval by the industry.

Radio Manufacturers to Curtail Use of Defense Metals

At a meeting of the Radio Manufacturers Association held in New York, N. Y., April 29, representatives of some 50 of the leading radio manufacturers entered into voluntary formal agreement to curtail sharply the use of aluminum and other metals necessary for National Defense. Use of aluminum alone, it is estimated, will be reduced 75 per cent for normal projected civilian production. The following agreements were adopted unanimously:

1. That the use of aluminum in the manufacture of radio sets be restricted to material for foil in the manufacture of capacitors, and to rotors in variable condensers. Under this agreement aluminum substitutes will be used for coil cans, condenser cans, tube shields, etc., when present aluminum supplies for such numerous radio components are exhausted.

2. Another unanimous industry agreement was that set manufacturers immediately will begin use of variable condensers having steel stators (instead of aluminum), and on and after June 15 will receive and use only condensers having stators of processed steel.

3. Another industry agreement was that set and speaker manufacturers will immediately discontinue purchase of aluminum and also nickel for permanent magnets for sets for domestic and export sale other than battery, portable, and farm sets that operate from batteries, and three-power (a-c–d-c) portable and farm sets. This involves drastic reduction in types and models of small radio sets using P.M. speakers containing aluminum and nickel.

Arrangements also were made for regulation and procedure to insure enforcement of the industry agreements.

New GE Windowless Building

Adding to the growing list of such structures, a one-story windowless building now is under construction at West Everett, Mass., for the General Electric Company, consisting of a main manufacturing section 500 by 400 feet with an attached boiler house, test, and forge shop 80 by 300 feet. It is scheduled for completion in July.

Providing more than five unobstructed acres of production floor space under one roof, the plant will be air conditioned and will be lighted by fluorescent units to an expected level of 50 foot-candles. Two 100-watt 60-inch fluorescent tubes mounted in continuous reflectors extending at frequent intervals the entire length of the building will furnish the illumination. The total lighting load is expected to be 600 kw.

So far the company's expansion program has called for an investment of well over 50 millions of dollars, according to the company's current quarterly report to stockholders. Some factory buildings already are completed, and 14 new buildings and additions are under construction and will be completed this year.

Westinghouse to Operate Navy Plants

The Westinghouse Electric and Manufacturing Company announces that it has been asked by the United States Navy to construct and operate two ordnance plants to manufacture armament equipment for the expanding Navy. The estimated cost is more than $20,000,000, and the buildings will be financed directly by the Navy. Machine tools and manufacturing facilities are expected to cost more than $11,000,000.

One of these plants is to be located at Canton, Ohio, and the other at Louisville, Ky. The Canton plant will consist of four manufacturing buildings, approximately 200 feet wide and 750 feet long, and a cafeteria and office building. They will have a manufacturing area of about 600,000 square feet. The Louisville plant will consist of five buildings, a cafeteria and office building, with a manufacturing area of about 500,000 square feet. All buildings are expected to be completed and ready to begin operations about July 1, 1941.

Educational Program Features Applied Mathematics

Beginning with a summer session which can be continued through the academic year 1941–42, a center where engineers, mathematicians, technicians, and other specialists in defense production can devote their full time intensively to problems of higher mathematics as applied to industry will be set up at Brown University, Providence, R. I., according to a recent announcement by President H. M. Wriston of the university.

Four courses in applied mechanics are to be offered—"partial differential equations," "fluid dynamics," "elasticity," and a seminar for weighing current research problems in elasticity and fluid dynamics. As applied to particular engineering problems, the work of the summer session will deal with highly specialized phases of aeronautics, stresses in machinery, ship construction, ballistics, and the detection of submarines and airplanes.

The program as a whole will become part of the engineering defense-training program of the United States Office of Education and is being aided by a grant of funds from the Carnegie Corporation of New York; no tuition fee will be charged. If the summer session is successful, Brown plans to introduce a full year of similar studies during 1941–42 and to offer fellowships ranging in amounts up to $600.

A maximum of 60 students will be accepted, according to Dean R. G. D. Richardson of Brown's graduate school, who is in charge of the program. All candidates must have already had considerable experience in various branches of higher mathematics, physics, and mechanics, amounting to the equivalent of a year's graduate study. Sessions will begin June 23 and will continue for 12 weeks until September 13. There will be five lectures a week in each course, and at least as much time will be given over to informal conferences.

Electric Power and Defense

"New construction already under way or planned by the electric utilities continues to mount in total and should keep the nation's electric generating capacity well ahead of any increased demand due to the defense program," according to a report in the March issue of Edison Electric Institute *Bulletin*. "At the end of 1940," the report continues, "the total installed capacity exceeded demand by 32 per cent, and the new construction should more than maintain this ample margin.

"Present schedules call for installation in 1941 and 1942 of 6,715,000 kw of new generating capacity, an amount approximately 30 per cent greater than was ever installed in any previous two-year period. Of this total, 6,354,000 kw is scheduled for central-station installation and the remainder in industrial plants.

"New central-station installations amounting to 3,397,000 kw of generating capacity announced for 1941 are being completed as scheduled. The generating capacity scheduled for installation in central stations in 1942 now totals 2,957,000 kw, this amount having been raised 655,000 kw since the first of the year. Additional capacity of 800,000 kw more is already scheduled for 1943, and 620,000 kw for 1944 . . . .

"Electric power output of recent months compared with corresponding figures of peak demands on generating plants reflects the longer working hours of munitions factories. From June to November peak demand increased at about the same rate as energy output. In December, January, and February, however, energy output increased 20 to 25 per cent faster than peak demand. This difference was most pronounced in the New England, Middle Atlantic, and Great Lakes States, in which increased energy output exceeded increased demand by more than 30 per cent. As the defense program advances further into the production stage, with two and three operating shifts becoming the rule in manufacturing

plants, this trend toward greater energy output from existing generating capacity will increase correspondingly."

Telephone Communication and Defense

In a prepared statement presented at the annual meeting of stockholders of the American Telephone and Telegraph Company, President Walter S. Gifford (A'16) called attention to the part the company and its affiliated organizations have been playing in the National Defense program, and to the various appointments of company officials to defense boards and committees of the Government.

Speaking of the additional telephone facilities that the company is being called upon to furnish, President Gifford said in part:

"While we are working at high pressure to give telephone service to the Army and Navy, and to provide other equipment for the two services, almost every other industry in the United States is also working on defense production. We have our part in that because as others increase the tempo of their efforts they inevitably use the telephone more and use more telephones, for the telephone is an instrument of speed and accuracy in modern affairs. And this means that we have a little part in almost every effort toward national defense. A little part in every effort adds up to pretty large figures.

"We have never yet had a net gain of as much as a million telephones in a year—last year's gain of 950,000 was the highest we ever had—but if the present rate of growth should continue throughout the year, we would gain nearly a million and a half telephones—50 per cent more than ever before in one year. In any case an increase of well over a million looks certain."

Government Needs Aeronautical and Mechanical Engineers

The production, development, and testing of aircraft and airplane engines is becoming of increasing importance in the national defense program. Four Government agencies are now seeking qualified engineers who can do the critical investigative and research work connected with the development of faster, safer, and more powerful airplanes. Aeronautical training is especially in demand, although much of the work now being done also requires the services of qualified civil, mechanical, and electrical engineers. The United States Civil Service Commission has announced open continuous examinations in all fields of engineering. Application forms (Form 8) may be obtained at any first- or second-class post office. The application, when properly filed, is rated immediately, and applicants rated eligible may be certified at once to an appointing officer, may be tendered an offer of employment by wire, and may be at work within a week of the time of filing applications.

The Air Corps now employs approximately 400 professional engineers at Wright Field, Dayton, Ohio, where most of the aircraft testing and developmental work of the War Department is concentrated. Many of these engineers in aeronautical and mechanical fields are engaged in checking the latest technical developments in aeronautical research and adapting and applying them to improved military aircraft. The Air Corps is particularly anxious to interest recent engineering graduates and senior students in the many opportunities afforded at Wright Field through the testing and checking of the latest advancements in airplane engine design.

The Navy Department now employs over 165 aeronautical engineers. The Bureau of Aeronautics is charged with responsibility for all that relates to the design, construction, fitting-out, testing, repair, and alteration of naval aircraft and aircraft instruments, equipment, and accessories.

The National Advisory Committee for Aeronautics conducts fundamental research on the problems of flight. The Committee's major research laboratory is located at Langley Field, Virginia, while a second laboratory is partially completed at Moffett Field, California. Current projects involve investigations requiring research in aerodynamics, hydrodynamics, aircraft structures, and aircraft engines; the results of research are available to Governmental agencies and to those units of the aircraft industry that are most concerned. The engineer personnel has increased rapidly in the last six months, and when the new Aircraft Engine Research Laboratory at Cleveland is completed, a still greater number of qualified engineers, particularly aeronautical and mechanical, will be needed. The present personnel includes a total of 340 engineers, of which approximately 50 per cent are aeronautical and 25 per cent are mechanical.

The Civil Aeronautics Authority, which is chiefly concerned with the inspection and development of nonmilitary air transport and airways, also concentrates on the testing and approval of developments in safety devices, instruments, and improved designs for all types of aircraft. Research is conducted at the Bureau of Standards in Washington, D. C., and at the experimental laboratory at Indianapolis; studies are made relative to the extinguishing and prevention of aircraft fires, and an improved system for "blind" landing. At present the Authority is employing over 300 engineers, of which over 20 per cent are aeronautical.

Airplane engine development has not yet reached the stage where little remains to be done. The race to improve aircraft design is now on an international scale and the importance of succeeding in the competition to develop the perfect plane cannot be overestimated. New discoveries are being made almost daily, and events in Europe are furnishing the most exacting trial conditions for the application of new theories to aircraft. Any new discovery may revolutionize some phase of production, if properly applied by qualified engineers who understand the present problems involved in engine and aircraft design, carburetion, cooling, accessories, instruments, fuels, lubricants, etc.

Each of the four agencies mentioned maintains research laboratories at which the major concern is the development of new testing methods to check the efficiency and practicability of current and proposed designs in aircraft and airplane engines. New fuels are being studied in relation to higher speeds, higher altitudes, and longer flights. New types of engines require new lubricants, new superchargers, better carburetion, better bearings. Designs are constantly being improved to allow speedier, more thorough overhauling and easier replacement and repair of worn or damaged parts.

Improvement in the design of aircraft is going ahead rapidly. The engineer is needed to check and test each new feature of design to offset factors of weight and strength against speed and guns and armor plate. Studies are being made of propeller design, engine cowlings, and airfoil design, to combine greatest speed with greatest stability and efficiency. Improved theoretical design must be applied in a usable manner to planes for service under the uncompromising conditions of modern warfare and modern transportation requirements. It is the responsibility of the United States Civil Service Commission to interest qualified engineers in the job to be done, and to furnish the Government agencies with the required personnel to carry on the program.

POSITIONS TO BE FILLED THROUGH CIVIL SERVICE EXAMINATION

Notice of the following positions, which will be filled through civil service examinations, is published here as a service to members of the Institute. Application forms and full information as to requirements for examinations may be obtained from the secretary of the Board of United States Civil Service Examiners at any first- or second-class post office, or from the United States Civil Service Commission, Washington, D. C.

Air Corps Procurement Inspectors. Through an examination announced some time ago, the Civil Service Commission has been seeking experienced men for procurement inspector positions in the Air Corps of the War Department. The Commission has not been able to obtain enough men for these positions. On the contrary, the needs have been extended to other fields than those in the original announcement. Five new fields in which persons may qualify have been added, and the options now are: Aircraft, engines, instruments, parachutes, aircraft propellers, tools and gages, radio, aircraft miscellaneous materials, textiles, fur-lined clothing, and optical. In general, mechanical experience, which may include apprenticeship, is required in the field applied for. For only four options (aircraft, parachutes, propellers, and aircraft materials) need this experience be specifically on aircraft materials. College courses in engineering may be substituted for part of the experience. Applicants will not have to take a written test, but will be rated on their experience and education. For details concerning the amended requirements applicants should consult Announcement No. 6-249 Revised of April 22, 1941. Original appointments will be made at salaries ranging from $1,620 to $2,600 a year. Opportunities for advancement are excellent. Applications may be filed until further notice with the Secretary of the Board of United States Civil Service Examiners at Wright Field, Dayton, Ohio.

Engineering Draftsmen. $1,800 a year; also: chief, $2,600; principal, $2,300; senior, $2,000; and assistant, $1,620 a year. Various optional branches. Applications will be rated as received at the United States Civil Service Commission, Washington, D. C., until December 31, 1941. Announcement previously published (*EE, Feb. '41, p. 91*) has been amended to include the optional branch statistical. There is need particularly for draftsmen qualified in the field of statistics. Information regarding the examination and the other optional branches of drafting for which applications are being received is given in the original announcement.

Industry • • • •

Westinghouse Issues New Magazine

First issue of the *Westinghouse Engineer*, a new quarterly in the field of engineering, published by the Westinghouse Electric and Manufacturing Company, appeared in May 1941. The periodical will be issued in February, May, August, and November, and is distributed to a selected list of engineers and executives of firms using electric power and equipment. It is also available by subscription. It contains no advertising.

According to announcement, the new magazine is planned to offer information on the generation, transmission, and distribution of electric power. Articles will be published on all phases of practical engineering involved in the selection, application, operation, and maintenance of electrical equipment. Charles A. Scarlott is editor, and J. George Adashko (A'34) assistant editor. Among the editorial advisors are R. C. Bergvall (A'24) and Tomlinson Fort (A'27, M'35). Authors represented in the first issue include S. G. Hibben (A'34), J. E. Hobson (A'36), H. V. Putman (A'23, M'32), C. W. Drake (A'20, M'21), and J. S. Parsons (A'27).

Commercial Television July 1 Authorized by FCC

Beginning of commercial television service July 1, 1941, under regulations embodying in substance the standards recommended by the National Television System Committee has been authorized by the Federal Communications Commission. The standards fix the line and frame frequencies at 525 and 30 respectively. Frequency modulation is required for the sound accompanying the pictures. Standards are to be allowed six months of practical test, after which further changes may be considered, particularly with reference to color television.

The Commission's regulations require a minimum broadcast program service of 15 hours a week by commercial television stations, not more than three of which may be under the same control. Action followed the public hearings of March 20–24, 1941 (*EE, Mar. '41, p. 145–7; May '41, p. 241*).

Utilities Add Generating Capacity

Additional generating capacity totaling 3,352,639 kw will be installed in the United States during 1941, according to reported preliminary results of a recent Federal Power Commission survey of the electric utility industry. Compared with 1,877,844 kw reported last year as scheduled for installation during 1940, this figure represents an increase of 78.5 per cent.

The report contains detailed data for scheduled additions to generating plants by privately and publicly owned utilities, subdivided by states and type of prime mover. The geographic summaries show that over 70 per cent of the hydroelectric generating equipment scheduled for installation during 1941 is to be located in the mountain and Pacific areas and is to be added by publicly owned utilities, while a majority of the scheduled steam generating equipment is to be constructed in the Middle Atlantic and East North Central areas by privately owned utilities.

Budgeted expenditures for generating plants of all types for 1941 total $387,517,000 and for all other electric plants $480,692,000, making a grand total of $868,209,000 for all electrical construction expenditures. Of this amount, the budgeted expenditures reported for privately owned utilities total $597,102,000 and those for publicly owned utilities $271,107,000. Comparison of construction expenditures with scheduled additions to generating capacity, by geographical areas, is shown in the accompanying table.

Comparison of Scheduled Additions to Generating Capacity and Electrical Construction Expenditures for 1941 and 1940

(As Reported at the Beginning of Each Year)

	Scheduled Additions to Generating Capacity			Total Electrical Construction Expenditures		
Geographic Division	Kw 1941	Kw 1940	Increase or Decrease (Per Cent)	1941	1940	Increase or Decrease (Per Cent)
UNITED STATES	3,352,639	1,877,844	+ 78.5	$868,208,950	$593,879,533	+ 46.2
New England	148,000	75,557	+ 95.9	45,614,593	34,421,291	+ 32.5
Middle Atlantic	532,566	332,950	+ 60.0	146,364,542	126,616,435	+ 15.6
East North Central	851,684	485,288	+ 75.5	212,107,213	162,305,362	+ 30.7
West North Central	136,017	162,192	16.1	52,259,448	35,901,942	+ 45.6
South Atlantic	507,358	445,256	+ 13.9	117,994,253	115,734,755	+ 2.0
East South Central	162,776	102,000	+ 59.6	97,241,025	20,728,151	+369.1
West South Central	90,059	107,546	− 16.3	31,497,201	26,842,812	+ 17.3
Mountain	293,117	29,055	+908.8	24,488,006	12,520,651	+ 95.6
Pacific	631,062	138,000	+357.3	140,642,669	58,808,134	+139.2

Expenditures of Electrical Industries Reported

TOTAL capital expenditures for plant and equipment by 1,354 establishments in the various electrical manufactures and related industries, in 1939, totaled $39,968,347, according to statistics recently announced by the United States Bureau of the Census.

The 1940 Census of Manufactures, covering operations of factories during the previous year, supplied the Census Bureau for the first time with information on such

Expenditures for Plant and Equipment for the Communication Equipment and Related Products Subgroup

	Total for Subgroup		Radios, Radio Tubes, and Phonographs Industry		Communication Equipment Industry	
	Number or Amount	Per Cent of Sub-Group Total	Number or Amount	Per Cent of Industry Total	Number or Amount	Per Cent of Industry Total
Total number of establishments	451	100.0	224	100.0	227	100.0
Number of establishments reporting capital expenditures for plant and equipment	324	71.8	152	67.9	172	75.8
Total value of products	$467,196,654	100.0	$275,870,165	100.0	$191,326,489	100.0
Value of products of establishments reporting expenditures for plant and equipment	441,577,395	94.5	262,892,939	95.3	178,684,456	93.4
Total expenditures for plant and equipment	9,127,979	100.0	4,912,141	100.0	4,215,838	100.0
Expenditures for new construction or major alterations of buildings and other fixed plant and structures	1,348,061	14.8	946,801	19.3	401,260	9.5
Expenditures for new machinery and operating equipment	7,387,359	80.9	3,783,551	77.0	3,603,808	85.5
Expenditures for plant and equipment acquired in a "used" condition from other owners and expenditures for land	392,559	4.3	181,789	3.7	210,770	5.0

Expenditures for Plant and Equipment for Four Industries in the Electrical Machinery Industry Group*

	Electrical Appliances Industry		Insulated Wire and Cable Industry		Automotive Electrical Equipment Industry		Electric Lamps Industry	
	Number or Amount	Per Cent of Industry Total	Number or Amount	Per Cent of Industry Total	Number or Amount	Per Cent of Industry Total	Number or Amount	Per Cent of Industry Total
Total number of establishments	138	100.0	79	100.0	84	100.0	55	100.0
Number of establishments reporting capital expenditures for plant and equipment	92	66.7	60	75.9	47	56.0	38	69.1
Total value of products	$145,696,194	100.0	$120,390,050	100.0	$109,761,620	100.0	$84,827,985	100.0
Value of products of establishments reporting expenditures for plant and equipment	138,824,453	95.3	118,764,552	98.6	105,682,477	96.3	83,488,824	98.4
Total expenditures for plant and equipment	2,278,948	100.0	2,594,507	100.0	2,676,894	100.0	2,646,550	100.0
Expenditures for new construction or major alterations of buildings and other fixed plant and structures	446,778	19.6	436,542	16.8	200,381	7.5	185,410	7.0
Expenditures for new machinery and operating equipment	1,677,080	73.6	2,058,509	79.3	2,449,157	91.5	2,450,327	92.6
Expenditures for plant and equipment acquired in a "used" condition from other owners and expenditures for land	155,090	6.8	99,456	3.8	27,356	1.0	10,813	0.4

*Each of these industries has the status of a subgroup.

Expenditures for Plant and Equipment for the "Electrical Equipment for Industrial Use" Subgroup*

	Total for Subgroup		Wiring Devices and Supplies		Carbon Products for the Electrical Industry, and Manufactures of Carbon or Artificial Graphite		Electrical Measuring Instruments		Generating, Distribution and Industrial Apparatus and Apparatus for Incorporation in Manufactured Products	
	Number or Amount	Per Cent of Subgroup Total	Number or Amount	Per Cent of Industry Total	Number or Amount	Per Cent of Industry Total	Number or Amount	Per Cent of Industry Total	Number or Amount	Per Cent of Industry Total
Total number of establishments	727	100.0	146	100.0	31	100.0	59	100.0	491	100.0
Number of establishments reporting capital expenditures for plant and equipment	494	68.0	111	76.1	21	67.7	33	55.9	329	67.0
Total value of products	$624,940,790	100.0	$94,305,273	100.0	$18,375,580	100.0	$41,797,495	100.0	$470,462,442	100.0
Value of products of establishments reporting expenditures for plant and equipment	601,794,905	96.3	90,702,038	96.2	15,798,092	86.0	40,073,943	95.9	455,220,832	96.8
Total expenditures for plant and equipment	16,733,489	100.0	1,936,535	100.0	648,234	100.0	1,327,629	100.0	12,821,091	100.0
Expenditures for new construction or major alterations of buildings and other fixed plant and structures	2,548,402	15.2	247,628	12.8	226,623	34.9	297,430	22.4	1,776,721	13.9
Expenditures for new machinery and operating equipment	13,691,920	81.8	1,607,955	83.0	351,190	54.2	1,027,947	77.4	10,704,828	83.5
Expenditures for plant and equipment acquired in a "used" condition from other owners and expenditures for land	493,167	3.0	80,952	4.2	70,421	10.9	2,252	0.2	339,542	2.6

*The four industries included are: wiring devices and supplies, carbon products for the electrical industry, and manufactures of carbon or artificial graphite, electrical measuring instruments, and generating, distribution, and industrial apparatus for incorporation in manufactured products, not elsewhere classified.

Expenditures for Plant and Equipment for the Electrical Products Not Elsewhere Classified Subgroup*

	Total for Electrical Products Not Elsewhere Classified Subgroup		Batteries, Storage and Primary (Dry and Wet) Industry		X-Ray and Therapeutic Apparatus and Electronic Tubes Industry		Electrical Products Not Elsewhere Classified Industry	
	Number or Amount	Per Cent of Subgroup Total	Number or Amount	Per Cent of Industry Total	Number or Amount	Per Cent of Industry Total	Number or Amount	Per Cent of Industry Total
Total number of establishments	480	100.0	221	100.0	84	100.0	175	100.0
Number of establishments reporting capital expenditures for plant and equipment	299	62.3	138	62.4	50	59.5	111	63.4
Total value of products	$174,576,656	100.0	$117,582,712	100.0	$17,945,038	100.0	$39,048,906	100.0
Value of products of establishments reporting expenditures for plant and equipment	162,466,547	93.1	113,117,878	96.2	16,702,544	93.1	32,646,125	83.6
Total expenditures for plant and equipment	3,909,980	100.0	2,319,018	100.0	294,045	100.0	1,296,917	100.0
Expenditures for new construction or major alterations of buildings and other fixed plant and structures	651,940	16.7	371,723	16.0	106,905	36.4	173,312	13.4
Expenditures for new machinery and operating equipment	3,127,865	80.0	1,893,666	81.7	171,952	58.5	1,062,247	81.9
Expenditures for plant and equipment acquired in a "used" condition from other owners and expenditures for land	130,175	3.3	53,629	2.3	15,188	5.1	61,358	4.7

*The three industries included are: batteries, storage and primary (dry and wet), X-ray and therapeutic apparatus and electronic tubes, and electrical products not elsewhere classified.

expenditures. Manufacturers were requested to report charges to capital account for new depreciable assets at cost value.

Expenditures for new machinery and operating equipment constituted the largest part of the capital outlays reported, with a total of $32,842,217. Outlays for new construction or major alterations of buildings and other fixed plant and structures totaled 5,817,514, while expenditures for plant and equipment acquired in a "used" condition from other owners and expenditures for land totaled $1,305,616.

The establishments reporting plant and equipment expenditures accounted for more than 95 per cent of the value of products made in the electrical manufactures and related industries. The total value of products reported by the 2,014 establishments grouped in the several industries was $1,727,389,949. Of this total, the 1,354 establishments reporting expenditures for plant and equipment, produced goods valued at $1,652,599,153. Data upon expenditures by the various classifications of electrical industries are given in the accompanying tables.

Honors

Award Established by Engineering Societies of New England

A new honor in the field of engineering, the "New England Award", presented this year for the first time, has been established by the Engineering Societies of New England, Inc. The award "is to be made not more than once a year to a living engineer, resident in New England, who by outstanding achievement has merited recognition of his work and character by his fellow engineers of the New England States." The recipient will be chosen from nominations of the constituent societies of the Engineering Societies of New England, Inc., and from the co-operating organizations allied with the Societies. The award was made this year to W. H. Pratt (A'02, F'13) retired consulting engineer, General Electric Company, Lynn, Mass. A biographical sketch of Mr. Pratt appears on page 294.

W. L. Batt Awarded 1940 Gantt Medal

The Henry Laurence Gantt Memorial Gold Medal for 1940 was awarded to William Loren Batt, deputy director, production division, Office of Production Management, Washington, D. C.

The medal is awarded annually for "distinguished and liberal-minded leadership in the art, science, and philosophy, of industrial management in both private and public affairs". It was established in 1929 through a fund raised by a group of friends of the late Henry Laurence Gantt, to commemorate his achievements in the field of industrial management. Selection of the recipient is made by a board made up of representatives of the American Society of Mechanical Engineers and the Institute of Management. First award of the medal was made to Mr. Gantt posthumously, in 1929.

A native of Salem, Ind., Mr. Batt received the degrees of mechanical engineer in 1907, and doctor of engineering in 1933, from Purdue University. He has been associated with the SKF Industries, Inc. and its predecessor the Hess-Bright Manufacturing Company since 1907, and has been president of SKF since 1923. He is a past president of the Society of Mechanical Engineers. Mr. Batt is chairman of the Business Advisory Council of the United States Department of Commerce; chairman of the division of engineering and industrial research of the National Research Council; chairman of the board of the American Management Association; and president of the International Committee on Scientific Management. He has been decorated twice by King Gustav V of Sweden for his work in promoting commercial relations between Sweden and the United States.

Other Societies

NFPA Creates Endowment Fund

"To help perpetuate a program for the reduction of loss of life and property by fire" an endowment fund for the National Fire Protection Association has been created by recent action of the board of directors. The purpose of the fund is to enable the Association to undertake worthwhile research projects and other activities not permitted under present budget limitations. It is proposed that the fund shall be derived from gifts and from bequests in wills by members of the NFPA and others interested in furthering its objectives.

National Science Fund Established

"To receive and administer gifts for the advancement of science", a National Science Fund has been set up by the National Academy of Sciences, F. B. Jewett (A'03, F'12), president, announced recently. The fund has been organized as the result of a three-year study of the present sources of financial support for fundamental research in science by a committee under the chairmanship of Doctor A. F. Blakeslee, of the Carnegie Institution, Washington, D.C. The study disclosed an urgent need of new resources of revenue, to supplement and replace sources diminished through the depression and other economic changes. The Fund will be directed by a joint board of 12 lay members and 20 scientists. Doctor William J. Robbins, director of the New York Botanical Garden, has been made acting chairman.

Future Meetings of Other Societies

American Association for the Advancement of Science. 108th meeting, June 23–28, 1941, Durham, N. H.

American Chemical Society. Annual meeting, September 8–12, 1941, Atlantic City, N. J.

American Physical Society. 242d meeting (Pacific Coast), June 18–20, 1941, Pasadena, Calif.
243d meeting, June 20–21, Providence, R. I.

American Society for Testing Materials. 44th annual meeting, June 23–27, 1941, Chicago, Ill.

American Society of Civil Engineers. Annual convention, July 23–25, 1941, San Diego, Calif.

American Society of Heating and Ventilating Engineers. Semiannual meeting, June 16–19, 1941, San Francisco, Calif.

American Society of Mechanical Engineers. Semiannual meeting, June 16–20, 1941, Kansas City, Mo.

Association of Iron and Steel Engineers. Annual convention, September 23–26, 1941, Cleveland, O.

Canadian Electrical Association. Annual meeting, June 25–27, 1941, Seigniory Club, Quebec, Canada.

Illuminating Engineering Society. Convention, September 22–25, 1941, Atlanta, Ga.

Institute of Radio Engineers. Summer convention, June 23–25, 1941, Detroit, Mich.

Society for the Promotion of Engineering Education. 49th annual meeting, June 23–27, 1941, Ann Arbor, Mich.

Letters to the Editor

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Total Security—a Challenge

To the Editor:

Are engineers to offer more than technical ability for the welfare of the United States? The many comments in the April and May issues of ELECTRICAL ENGINEERING seem to prove without question that perhaps for the first time we, as a class, are accepting the responsibilities not only of machines but of directing our basic progress in defense.

Mr. Skinker, on page 194 of the April issue, has boldly challenged the inventiveness of all of us in making suggestions, small as they may seem, to safeguard production as a whole. Certainly today is no time for shyness because if all but one out of a thousand ideas are foolish, still a single plan is invaluable.

Those of us fresh from college are painfully aware of one handicap in the widely accepted plan to condense the time required to graduate: many students depend upon summer times to earn enough for further studies. What can circumvent this diffi-

culty is questionable. Perhaps our industries can arrange to give practical experience to such students in the summer period so as better to prepare students for positions after graduation, and even shorten the time needed for such study in the university.

To help stimulate thinking I would like to offer a few suggestions for discussion:

1. Perhaps now is the time to think of safeguarding valuable operating drawings and records by keeping duplicate prints where damage from fire, etc., to the originals cannot hinder production.

2. Many records could be preserved by photographing in miniature on roll film; maps with color codes might be photographed in Kodachrome and provision made for projecting the maps through a frosted translucent screen for inspection in emergency, if the originals should be lost.

3. The fire protection of automatic CO_2 extinguisher systems so carefully applied to plants might well be installed near essential prints and other perishable equipment. At the same time some of our antique wooden cabinets may be retired honorably from long service, and fire-resistant units substituted.

4. Better to acquaint engineers with the many night courses now offered, possibly our organ could act as a clearing house of such data, indicating local references. The few companies not offering such information to their technical employees ought to join the majority.

5. Maybe each of us in his own small way can inform his acquaintances of the genuine shortage of trained men, thus contributing to the end where every man may work to the peak of his ability and limit of his knowledge. Efficiency in the utilization of skilled men will be the backstay of defense in the testing period facing us.

William C. Urlovic (Enrolled Student)

(Electric department, Pacific Gas and Electric Company, San Francisco, Calif.)

Engineers and the Draft

To the Editor:

More than six months ago the first draftees filled out their questionnaires and were classified. On the whole, most of us will agree that the workings of the Selective Service Act during that time have been satisfactory. Some 4,000,000 men between the ages of 21 to 35 inclusive have been classified, and, according to a recent news report, 402,000 are serving in the military forces.

How have electrical engineers fared in the draft? Of the 18,000 members of the AIEE, one-third will receive draft questionnaires. Considering the whole electrical-engineering group of about 60,000* the draft includes an aggregate of 20,000 electrical engineers. If the draft law is revised to include only those from ages 21 to 26 inclusive, 8,000 electrical engineers still will receive questionnaires.

Draft boards throughout the country are now in the process of assigning these 20,000 engineers to classes I, II, III, and IV and their subdivisions. Only those classed in I*A* as "fit for general military duty" are being sent to training camps. Class II*A* includes those deferred because of occupation, who otherwise would be placed in class I*A*. Those with dependents are placed in class III*A*, while class IV*A* includes miscellaneous deferments.

Of the 20,000 engineers receiving questionnaires, many will be placed in class III*A* and can continue in their jobs without interruption. A large number, however, are single, without dependents, and, unless recognition is given to their occupational status, will be called to serve a year in camp. If this happens, the loss of trained engineers at a time when they are greatly needed will hinder rather than help the defense program.

Is such recognition being given? The answer varies widely with different draft boards. Some have been quick to see the importance of the engineer in his job, and to grant occupational deferments. Others, however, do not appear to see how electrical engineering has anything to do with defense.

One board, situated in a western state, gave a two months' deferment to a young engineer who was testing equipment, of which fully one-third was marked "for defense". When his two months' deferment expired, a second request brought him a second deferment—for two months. Considerable correspondence, in addition to the regular request for deferment which outlined his duties, was needed to show the board the importance of this test engineer's job.

Another draft board, in a midwestern state, delayed two months over the questionnaire of another test engineer, until the deferment request, also complete in its description of the man's duties was supplemented with a two-page letter. The board then stated that it had delayed classifying the man until further information was obtained as to his duties in the defense program. Since that information had now been supplied, the board place him in class II*A* for six months, with privilege of renewal.

Still another draft board, this time in the south, rejected the occupational deferment claim filed by one of these young test men, even though he was testing Navy turbines. After further correspondence, the board reconsidered and placed him in class II*A* for six months, the maximum period of deferment.

A New York draft board placed in class I*A* a graduate chemist who is developing a domestic synthetic substitute for an imported material whose source is threatened. Although newly engaged, he had previous experience to make him immediately effective on his job. These facts were clearly stated on the deferment request, which was supplemented by the chemist's personal appearance before the board. Nevertheless, he was placed in I*A*. He then presented his case to an appeal board which, up to the present, has not acted on it.

These examples are not cited to criticize the work of the draft boards. The members of these boards are, in the writer's opinion, sincere private citizens acting from patriotic motives. They are faced with difficult decisions. Their mistakes in most cases have been caused by a lack of sufficient general information.

Many employers likewise do not have sufficient perspective to act wisely on the question of deferments. One of the most promising young mechanical engineers of the writer's acquaintance recently was drafted and is doing routine service. He could be doing effective mechanical engineering work in an industrial company or in naval architecture. Evidently his employer failed to act, nor did the draft board voluntarily give him a deferred status, although it had the power to do so.

In another instance an electrical engineer was employed by a steel company on maintenance engineering when he received his questionnaire. The plant was in a period of expansion and the services of the maintenance organization were needed. The importance of the steel industry to the rearmament program is obvious. The employer did not ask for deferment and the young man was placed in class I*A*. Later he obtained similar engineering work with another company. Upon request of his new employer, the draft board re-classified him, placing him in II*A*.

It is not always the draft board or the employer which lacks information. In some cases, the individual is unaware of his obligation under the Selective Service Act. An electrical engineer with three years training had left college and was employed in industry. When he received his questionnaire he failed to inform his employer, although asked to do so. No deferment was requested until the employer learned of the situation ten weeks later. The draft board then rejected the claim, stating that the time to appeal the classification had expired.

That a shortage of trained engineers exists is evidenced in many ways. Industries are expanding their quotas for young engineers. Recruiting at the colleges is more active than ever. The placement bureaus report a steady demand for engineers during the past year. The United States Office of Education has recognized the lack of graduate engineers and has formed a Bureau of Engineering Defense Training. Courses of college grade, 12 weeks in duration, are being offered this summer at many colleges to train men in machine design, production engineering, metallurgy, material testing and inspection, chemistry, and other subjects.

Such programs underline the fact that it is a mistake to allow trained men to be drafted as privates when there are not enough skilled engineers to meet defense production requirements.

Some professional groups have already recognized the problem. The New York Academy of Medicine has gone on record as urging deferment of students in approved medical schools and of medical graduates working as internes. The American Chemical Society since last October, has been educating its members and the public through its periodicals and in the newspapers concerning the lack of trained chemists. Other chemical publications have featured similar articles. Through such publicity, misapplications of technical personnel, due to lack of sufficient information by employers, by the individual himself, or by the draft boards, will be eliminated.

In undertaking such a program it must be recognized that the Selective Service Act provides that:

> "No deferment from training and service shall be made in the case of an individual except upon the basis of the status of such individual, and no deferment shall be made of individuals by occupational groups or groups of individuals in any plant or institution."

While each individual case must be considered on its own merits, better decisions will be made if everyone appreciates the

* The Promise of Tomorrow. Walter E. Myer and Clay Moss, Civic Educational Service, Washington, D. C.

increasing demand for additional trained engineers and realizes the difficulty of locating adequate replacements for those who are drafted.

It is not within the scope of this letter to discuss methods by which the quotas for 1*A* men will be met. So far the draft boards have been able to solve that problem. One Massachusetts draft board reported in April that it had classified only 37 per cent of the young men who had registered, and had a reserve supply of 1*A* men not yet inducted into service. Also, only those in class 1*A* are being called for duty. Men in class 1*B*, "fit for limited military service", are not being inducted. This class constitutes from 8 to 24 per cent of those examined by the boards. Colonel Samuel J. Kopetzky, chief of the medical division of the New York City Selective Service, states that many of the 1*B* men in his area have easily remediable defects and suggests that steps could be taken to make this group fit for service.

Many engineers hold commissions in the Officers Reserve Corps. Some already are serving in the Army; others will be called to duty during the coming months. Engineers are also members of the Naval Reserve and National Guard. As a group they are well represented in the armed forces of the United States.

If skilled engineers are drafted as privates, it will not be the fault of the Selective Service organization, which has expressed its approval of deferring skilled employees, in newspaper releases which point out that at present production must have priority.

By this time the solution to the draft problem is probably obvious. It requires education by professional engineering societies and other groups which will reach employers, individual engineers, and the draft boards. Such education should be national in scope. It should appear in engineering journals and in newspapers. The question should be a topic of discussion at conventions.

A program of this type should continue until it obtains recognition. It should be endorsed by national engineering organizations and by educational institutions whose prestige will carry weight with the general public.

Such an undertaking will be a real service. It will clarify the task of the draft boards; employers of technical men will be benefited; and the individual engineer will be allowed to remain on his job where, at present at least, he is most effective in the defense program.

W. S. Fielding (A'38)

(Pittsfield, Mass.)

Books Received •

"Student and Employee Safety in Colleges and Universities". Published by the National Safety Council, Inc., this booklet deals with safety problems encountered in American educational institutions, a field where there are no laws making administrators responsible for safety of students. Contents of the booklet include: Organization to prevent accidents; fundamentals of accident prevention; inspecting for safety; standards for safety; safety in athletics; and campus traffic safety. The booklet contains 82 pages and is illustrated. Copies may be obtained at $1.00 each from the National Safety Council, Inc., 20 North Wacker Drive, Chicago, Ill.

"The Wheeler Project". The second Tennessee Valley Authority technical report deals with planning, design, and construction of the Wheeler Project on the Tennessee River. The first report was "The Norris Project", published in 1939. The book includes a description of the initial social and economic investigations necessary for the project; discussion of the designs of lock, dam, and powerhouse; a study of access roads and housing for employees; description of construction methods and reservoir adjustments; summary of initial activities; and an analysis of construction costs. Appendixes contain a statistical summary of the physical features of the project, copies of the reports of engineering and geologic consultants and summaries of special tests. Copies of the 362-page illustrated report may be obtained from the Superintendent of Documents, Washington, D. C., price $1.00 per copy.

"Insulation of Electrical Apparatus". Planned as a textbook on insulation for electrical engineering students interested in design and operation of power machinery, this study by Douglas F. Miner is a survey of several phases of the problems of dielectrics. It contains a résumé of the essential concepts of the nature and behavior of dielectrics; a description and comparison of insulating materials; discussion of the practices in application of insulation to the major types of power apparatus; and a description of testing methods and equipment. Appendixes contain tables and curves showing properties of certain classes of insulation. McGraw-Hill Book Company, New York, N. Y.; 452 pages, illustrated, price $5.00.

The following new books are among those recently received at the engineering Societies Library. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books in question.

ADVANCED ELECTRICAL MEASUREMENTS. By W. C. Michels. Second edition. D. Van Nostrand Company, New York, 1941. 347 pages, illustrated, 9 by 5½ inches, cloth, $3.50. In addition to standard methods and apparatus of the electrical laboratory, covers the application of instruments essentially electrical in character to the measurement of other physical quantities. Among alternative methods or instruments the author describes those which he has found satisfactory from personal experience. New edition is thoroughly revised, particularly in regard to application of electronic methods.

ANALYTICAL DESIGN OF HIGH-SPEED INTERNAL-COMBUSTION ENGINES. By F. M. Cousins. Pitman Publishing Corporation, New York and Chicago, 1941. 226 pages, diagrams, etc., 9 by 6 inches, cloth, $3.50. After reviewing thermodynamic cycles, the author proceeds to a detailed study of the dynamics of high-speed engines. In-line, *V*-type, radial, and offset cylinder engines all are considered in the discussion of engine balance and the analysis and design of cams, crankshafts, etc. Analysis has been restricted to the calculus and simple harmonic theory. Bibliography.

APPLIED HEAT TRANSMISSION. By H. J. Stoever. McGraw-Hill Book Company, New York and London, 1941. 226 pages, illustrated, 9½ by 6 inches, cloth, $2.50. Aims to provide in readily usable form for engineers some of the more important data on heat transmission and to describe some of the common types of equipment for transferring heat and kinds of insulation used in industry. Charts and tables for determining convection coefficients and values of the pressure drop are included.

THE CHEMICAL ACTION OF ULTRAVIOLET RAYS. By C. Ellis and A. A. Wells; revised and enlarged edition by F. F. Heyroth. Reinhold Publishing Corporation, 1941. 961 pages, illustrated, 9½ by 6 inches, cloth, $12.00. Advances in the field of photochemistry in the 16 years since this monograph first appeared have necessitated rewriting and expansion in the new edition. Part one describes the types of apparatus available for producing ultraviolet rays; part two deals with photochemical reactions; part three with the uses of photochemistry in industry; and part four with applications in biology. Bibliography.

COMMERCIAL REFRIGERATION AND COMFORT COOLING. By S. C. Moncher. Nickerson and Collins Company, Chicago, Ill., 1940. 109 pages, illustrated, 9½ by 6 inches, cloth, $1.50. A brief, nonmathematical description of commercial refrigeration as used in retail shops and restaurants, with emphasis on engineering methods in common use. Intended for those with a general knowledge of the field, who wish definite information upon equipment and its installation. Air conditioning is considered briefly.

DESIGN OF SHADING COILS FOR ALTERNATING-CURRENT ELECTROMAGNETS. By L. A. Doggett and F. S. Veith. Pennsylvania State College Engineering Experiment Station Bulletin No. 52, State College, Pa., 1940. 24 pages, illustrated, 9 by 6 inches, cloth, $0.50. Contains complete instructions for the design of a shaded-coil a-c electromagnet, with special reference to minimizing vibration by proper selection of shading-coil resistance. Short bibliography.

ELECTRIC AND MAGNETIC FIELDS. By S. S. Attwood. Second edition. John Wiley and Sons, New York, 1941. 430 pages, diagrams, etc., 9½ by 6 inches, cloth, $4.50. Presents the fundamentals of electricity and magnetism in a manner intended to co-ordinate elementary college study of mathematics, mechanics, and physics with the professional studies of the last two college years. Revised to provide background for courses in electronics, electrical design, and machinery. The four parts cover, respectively, the electric field, the magnetic field, the ferromagnetic field, and combined fields.

ELEKTRISCHE KIPPSCHWINGUNGEN, WESEN UND TECHNIK. (Physik und Technik der Gegenwart, volume 8.) By H. Richter. S. Hirzel, Leipzig, 1940. 154 pages, diagrams, 9 by 6 inches, paper, 10 rm. Describes the nature, method of generation, transference and intensification, and methods for technical analysis of relaxation oscillations in electrical apparatus. The final chapter indicates applications to electrotechnical and other technological fields. Bibliography.

GENERATING STATIONS, ECONOMIC ELEMENTS OF ELECTRICAL DESIGN. By A. H. Lovell. Third edition. McGraw-Hill Book Company, New York, 1941. 471 pages, illustrated, 9 by 6 inches, cloth, $4.50. Applies economic principles to design of generating stations and transmission systems, considering selection and application of apparatus, proportioning of details of the assembly, balancing of initial and subsequent costs, and related topics. New edition, revised in the light of recent developments. Illustrative problems.

INDUSTRIAL RELATIONS DIGESTS: I. THE ORGANIZATION OF A PERSONNEL DEPARTMENT. II. THE EMPLOYMENT DIVISION. III. REORGANIZATION OF HOUR SCHEDULES. Princeton University, Industrial Relations Section, Princeton, N. J., 1941. Each 7 pages, tables, 10 by 7 inches, paper, $0.20 each. Three pamphlets prepared for use in companies facing rapid expansion because of defense orders. They are based on information received currently from a large number of representative companies. A more complete study of the subject matter of III is in preparation.

MATHEMATICS FOR ENGINEERS. By R. W. Dull. Second edition. McGraw-Hill Book Company, New York and London, 1941. 780 pages, diagrams, etc., 8½ by 5½ inches, cloth, $5.00. A review of the phases of mathematics especially important in engineering, intended as a practical reference work or a text for private study. The chapter on the slide rule has been extended in this edition.

AMERICAN PLANNING AND CIVIC ANNUAL 1940. Edited by H. James. American Planning and Civic Association, Washington, D. C., 1940. 278 pages, illustrated, 9½ by 6 inches, cloth, $3.00. The papers collected in this volume constitute a record of recent civic advance in the fields of planning, parks, housing, and neighborhood improvement. About half the material was prepared especially for the Annual; the remainder consists of the principal papers delivered at the 1940 National Conference on Planning and the 19th National Conference on State Parks, 1940.

Transactions

Preprint of Technical Papers Comprising Pages 1–40 of the 1941 Volume

A Push-Button-Tuned 50-Kw Broadcast Transmitter

R. J. ROCKWELL
NONMEMBER AIEE

H. LEPPLE
NONMEMBER AIEE

Synopsis: This paper describes the use of automatic push-button tuning on short-wave broadcast transmitters that are required to change from one frequency to another with the least possible interruption to programs. The tuning control circuits and the arrangement of the radio-frequency circuits of the transmitter are described.

THE effective use of high frequencies for international radiobroadcasting requires the transmitter to use a frequency which will place the strongest signal in the selected service area. Since the best frequency to use will vary throughout the day, and since it may be desirable to shift the signal from one area to another, a transmitter built for international broadcasting should be able to change frequencies easily and rapidly.

Ordinarily a shutdown period is necessary to retune the transmitter whenever the frequency is changed. In the past when it has been necessary to change frequencies rapidly, as for instance during the short interval between programs, it has been customary to use a second transmitter tuned to the new frequency and then shift transmitters. This cumbersome procedure can be avoided if the tuning process is speeded up by the use of automatic devices. Retuning the transmitter is then a matter of seconds and is accomplished by simply pushing a button.

Description of Transmitter

The 50-kw WLWO transmitter of The Crosley Corporation employs automatic push-button tuning and a description of this transmitter will illustrate the practicality of this method of tuning.

The transmitter is designed to operate on any one of eight different frequencies. Figure 1 is a circuit diagram of the radio-frequency section of this transmitter. The radio-frequency amplifier up to and including the one-kilowatt stage is mounted on one chassis. Since the coils and capacitors for the grid and plate circuits of these stages are small, a separate set of coils and capacitors is used for each frequency. These coils and capacitors are mounted on a drum which is rotated by a motor until the proper tuned circuits make contact with a set of fixed wipers. The eight crystals are mounted separately and are kept at operating temperature at all times. When the drum rotates to bring into position the coils for a particular frequency, it also makes connection to the crystal for that frequency.

The plate coil of the 5-kw stage and grid coil of the 50-kw stage are too large to employ the preceding method of tuning. These circuits are tuned, therefore, by means of motor-driven wipers mounted on a shaft which runs through the center of the coil. The shaft is arranged to rotate the wipers in opposite directions. As the shaft turns the wipers slide along the turns of the coil, traveling from the middle toward each end. The wipers short-circuit a certain number of turns of the coil depending upon the frequency to be used. Figure 2 is a picture of the plate coil of the 5-kw stage. The rotating drum and the wipers on both the 5-kw tank circuit and the 50-kw grid circuit in addition to being motor driven may be rotated by a hand wheel mounted on the front of the transmitter cabinets. This arrangement is necessary to adjust the tuning system as described later in this paper.

The 50-kw amplifier employs a transmission-line tank circuit. This trans-

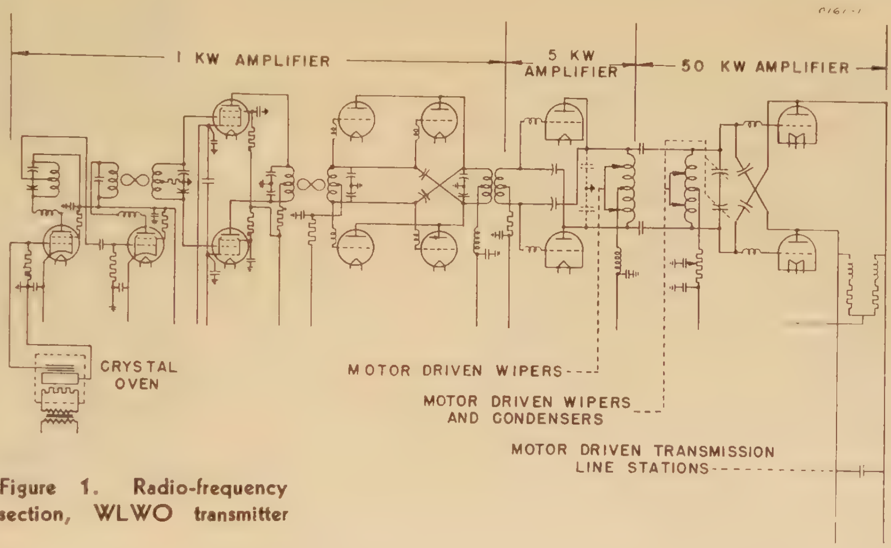


Figure 1. Radio-frequency section, WLWO transmitter

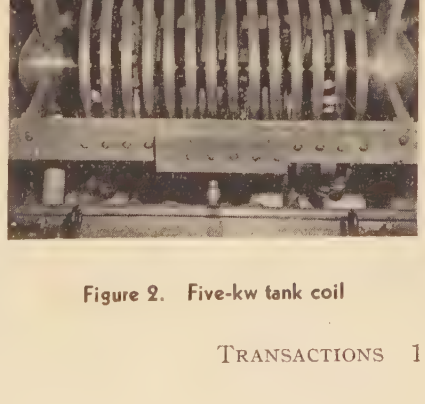


Figure 2. Five-kw tank coil

Paper 40-161, recommended by the AIEE committee on communication, and presented at the AIEE Middle Eastern District meeting, Cincinnati, Ohio, October 9–11, 1940. Manuscript submitted August 12, 1940; made available for preprinting September 10, 1940.

R. J. ROCKWELL, member IRE, and H. LEPPLE, associate member IRE are with WLW, Crosley Radio Corporation, Cincinnati, Ohio.

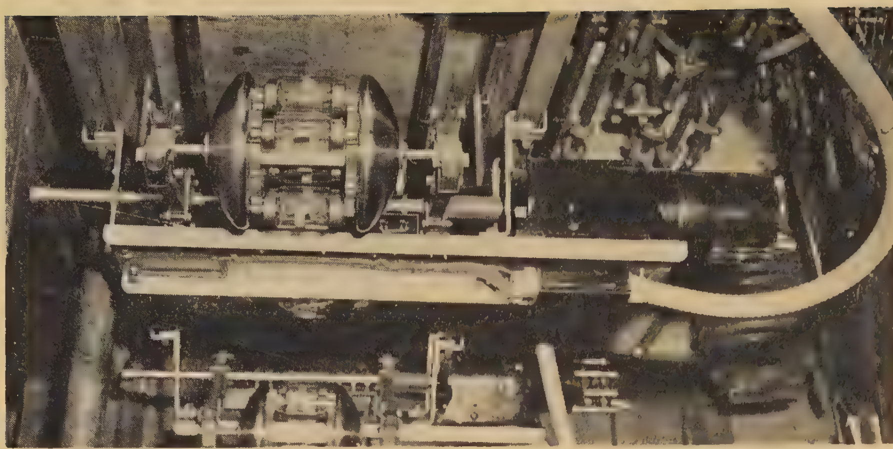


Figure 3. Transmission-line station

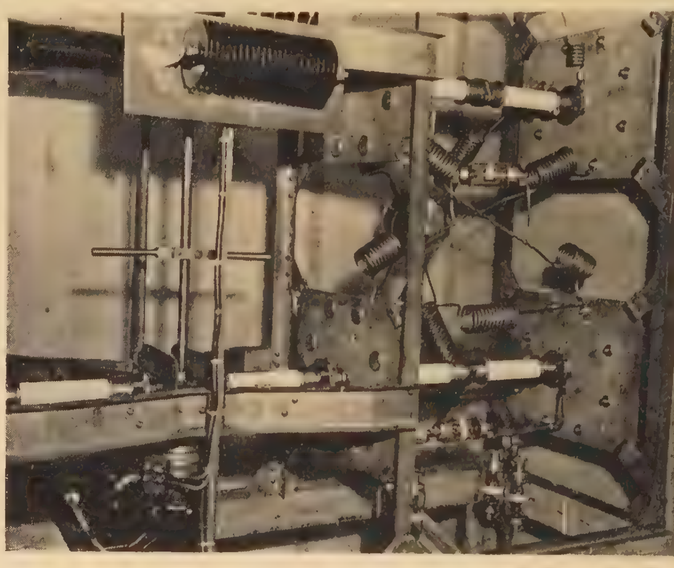
mission line is designed to present the proper load impedance to the final amplifier and also couple the antenna load to the transmitter. This is accomplished by switching across the transmission line at the proper point a capacitor of such size as to obtain the desired coupling. If eight different frequencies are used, there will be eight stations along the transmission line. Each station will consist of a group of vacuum capacitors that can be swung into contact with the transmission line by a motor. The capacitors are mounted on Mycalex arms which are swung from a horizontal position through 90 degrees to a vertical position where the capacitors make contact with the transmission line. When changing frequencies, the capacitors for the frequency on which the transmitter has been operating will swing away from the transmission line at the same time that the capacitors for the new frequency swing into contact with the line. Figure 3 is a picture of the WLWO transmission line showing the capacitor stations.

In addition to tuning the various tank circuits, it is necessary to match the antenna to the transmission line for each frequency. The circuits necessary for doing this are brought to contacts mounted on Mycalex plates. Wipers are rotated by a motor to select the circuits for the frequency to be used. Figure 4 shows the method of mounting these coils and the selecting mechanism. A portion of the coils have been removed to simplify the picture. This equipment is located in the antenna coupling house, some 200 yards from the transmitter building.

Tuning Control Circuits

From the preceding description it is evident that five operations must be completed to retune the transmitter. The drum on the 1-kw chassis must rotate to the proper set of coils, the wipers on the 5-kw tank coil and the wipers on the grid coil of the 50-kw stage must each move to a new position, a different capacitor station along the transmission line must swing into position, and the antenna must be matched to the transmission line.

Figure 4. Antenna matching mechanism



Each of these operations, except the tuning of the transmission line, is carried out by a rotating drum, a rotating switch, or a rotating wiper. The problem is to control these rotating devices so that they will turn through the shortest path to their new position and stop. To do this, three-phase motors and the motor reversing circuit illustrated in figure 5 were used. D is a bakelite disk mounted on a shaft which is mechanically connected to the rotating drum or wiper arms. This disk has a pin protruding from its side which engages the switch arm as shown in the diagram. If this disk is turned clockwise the switch arm will take the position shown in A and the circuit will be completed through the upper spring contact to relay number 2. However, if the disk is turned counterclockwise, as shown in B, relay number 1 will be operated and the motor will be reversed.

If the disk is in position A when the switch in P_1 is closed, relay number 2 will operate and the motor, being connected to rotate the disk counterclockwise will turn the disk until it is in position C when the relay will be released and the motor will stop. Likewise, when the disk is in position B when P_1 is closed, the motor will rotate in the reverse direction turning the disk clockwise until position C is reached.

If it is desired to have the motor stop at any one of eight positions, eight of these disks will have to be mounted on the shaft. For eight positions the circuit will be as shown in figure 6. Each of the eight "disk-switches" will make connection to either relay number 1 or number 2 depending upon whether the wiper will have to rotate clockwise or counterclockwise to reach its position. To select one of the eight positions it is only neces-

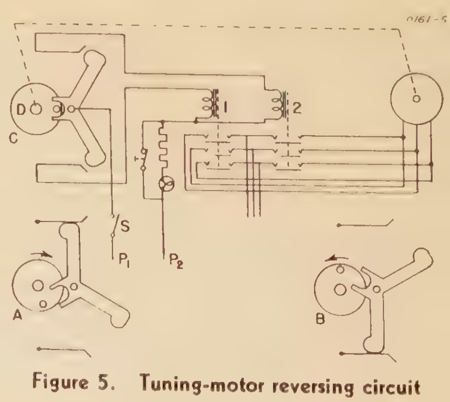


Figure 5. Tuning-motor reversing circuit

sary to close one of the eight switches S_1 through S_8, figure 6.

In applying the above system to WLWO it was necessary to control four motors in the above manner. To do this the circuit shown in figure 7 was devised. Eight frequency-selecting relays replace the switches S_1 through S_8 of figure 6. Each relay has a normally open contact for each of the motors that is to be controlled, that is, four normally open contacts. For simplicity only one tuning index and one transmission line station is shown connected in figure 7. The three tuning motors and the seven transmission line stations that are not shown are connected to the remaining normally open contacts in a similar manner. Each of the frequency relays may be "locked in" by pressing the proper frequency button as shown in figure 7. When one of these relays is "locked in", one of the disk-

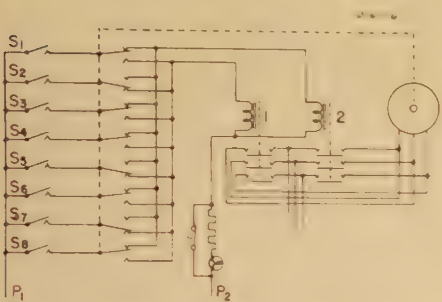
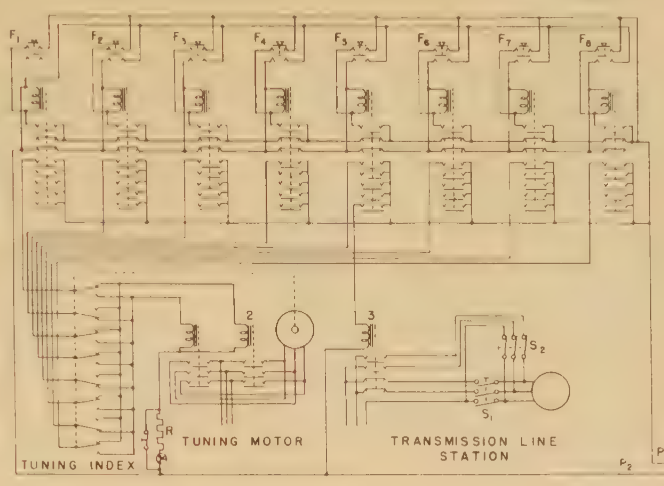


Figure 6. Eight-position motor control circuit

switches on each of the four motor index systems is energized and each of the four motors will rotate to its position and stop. It will be noted in figure 7 that the push buttons and the relay holding circuits are designed so that when a relay is "locked in" by pressing one of the buttons, the relay previously "locked in" is released. This arrangement makes it unnecessary to use an off button to release the previous frequency.

Figure 7 also shows the control circuits for the transmission line stations. Relay number 3 is used to reverse the motor phases. When this relay is not energized the phases are connected to rotate the capacitors away from the trans-

Figure 7. Push-button-tuning circuit



mission line. A limit switch operated by a cam on the rotating capacitor arms stops the motor. When the relay is energized the motor is connected to swing the capacitors into contact with the transmission line and again the motor is stopped by a limit switch. Each motor is equipped with a magnetic brake which is needed to bring the motor to a quick stop after the power is disconnected.

Adjusting the Tuning System

Referring to figure 5 it will be seen that a resistor and a six-volt bulb are connected in P_2 of the relay circuit. A switch is shown short-circuiting the bulb and resistor. If this switch is opened and the "disk-switch" is in either position A or B the lamp will burn but the relay will not pull in because of the voltage drop across the lamp and resistor. If the disk is turned the lamp will go out when position C is reached. The bakelite disks shown in figure 5 are held by friction to the shaft which is connected to the wipers and are arranged so that they will slip when turned by hand.

The procedure for adjusting the tuning system is as follows: First, the short-circuiting switch is opened and one of the frequency buttons is pressed to lock in one of the frequency relays. Next, the transmitter is tuned manually. This is done by rotating the wipers by hand, using the hand wheels provided for this purpose, until resonance is reached. Then, the bakelite disk is rotated, slipping on its shaft while the wiper arms are held stationary, until the light goes out. The short-circuiting switch is then closed and the transmitter is ready to tune automatically to this frequency. The same procedure must be followed for each tuning motor and for each frequency. A different push button and its associated "disk-switch" will be used for each frequency. After each of the tuned circuits is adjusted as just described, the entire transmitter will retune to any one of the eight frequencies by simply pressing the proper button.

An Improved Type of D-C Wattmeter of the Shunted Type

PAUL MacGAHAN
MEMBER AIEE

Synopsis: While wattmeters for high current values of a-c power are universally used in connection with instrument transformers, d-c power is ordinarily measured by using separate ammeters and voltmeters on account of the difficulty in making a heavy-current d-c wattmeter. Although large direct currents are conveniently measured by use of the shunt and millivoltmeter, shunted-type d-c wattmeters have in the past been somewhat unsatisfactory.

An improved d-c wattmeter is described which corresponds in accuracy and sensitivity to the usual permanent-magnet moving-coil ammeter and operates from the usual ammeter shunt.

THE measurement of power in a d-c circuit is generally accomplished by the use of separate ammeters and voltmeters. This has been acceptable for most d-c conditions because a simple multiplication of amperes and volts gives the correct power. Furthermore, the construction of a direct-reading d-c wattmeter for large currents has heretofore involved great difficulties in construction and installation.

In certain cases where the voltage is variable, it would be distinctly preferable to read the watts directly. The instrument described is designed to fill this need.

D-c wattmeters for low values of current can be satisfactorily designed using the electrodynamic principle with a stationary coil carrying the entire current and a moving coil in the voltage circuit. The practical limitations of this construction are due to the difficulty in constructing the series coil for currents in excess of about 400 amperes capacity, as well as the matter of the heavy and expensive leads required to bring the current to the terminals of the instrument. A minor difficulty is to avoid residual magnetization errors because the heavy currents tend to magnetize the metal cases and internal magnetic shields.

The reason these difficulties do not exist in the case of measuring d-c amperes is because the permanent-magnet moving-coil principle requires a very low power level of operation, compared with the power taken by instrument coils of any instrument using other principles. Whereas an ordinary portable or switchboard-type electrodynamic wattmeter without iron cores requires a power level of the order of one or two watts to energize the current coil, the coils of corresponding permanent-magnet moving-coil movements of normal sensitivity take only 0.0004 watt and when one of the newer types of high coercive magnet steel is used, the power level may be much less.

It is this unique quality of the permanent-magnet moving-coil type instruments[1] which permits their use as shunted ammeters, with shunts having the usual standard drop of only 50 millivolts. In order to make a shunted-type coreless electrodynamic wattmeter for 10,000 amperes with the same ratio of copper to swamping resistance, and consequently the same temperature error as in the d'Arsonval ammeter, would require a shunt consuming at least five or six kilowatts.

It is not unusual to mount instruments on switchboards, 50 or more feet from the bus-bar structure. Such long leads still further increase the resistance, and consequently, the power required in the shunt.[9]

Another difficulty attending attempts to operate such wattmeters from ammeter shunts is that in order to obtain a sufficiently large current in the shunted-coil circuit, the resistance of the coil and of the leads must be made very low. Thus, any contact resistance in the connections introduces a variable which causes a considerable error in the readings.

However, such shunted-type electrodynamic wattmeters have been built, generally by the expedients of reducing the ampere turns of the series coils to subnormal values and obtaining a torque subnormal in value but yet sufficient to operate the movement by working the voltage coils much harder in proportion. This involves considerable compromise in the direction of allowing much higher temperature errors in both the moving-coil and current-coil circuits. The constants of one wattmeter of this construction are shown in column *A* of table I. Such designs can be regarded only as compromises.

The desirability of finding other means as a solution of the general problem of heavy-capacity d-c wattmeters became apparent from the data given in column *A*. Several other possibilities were studied and the investigations led to the design of the type of instrument described further in this paper.

It should be noted that a desirable element of the problem from an economic viewpoint was the necessity of utilizing to as great extent as possible, existing instrument mechanisms, because the probable applications are not so large as are those of other instruments; moreover, commercial instruments can be built economically only with the aid of expensive tool equipment. Uniformity in appearance with other switchboard instruments was another desideratum.

These considerations led to the belief that the most practical solution might lie in substituting an iron-core electromagnet for the usual permanent magnet of the

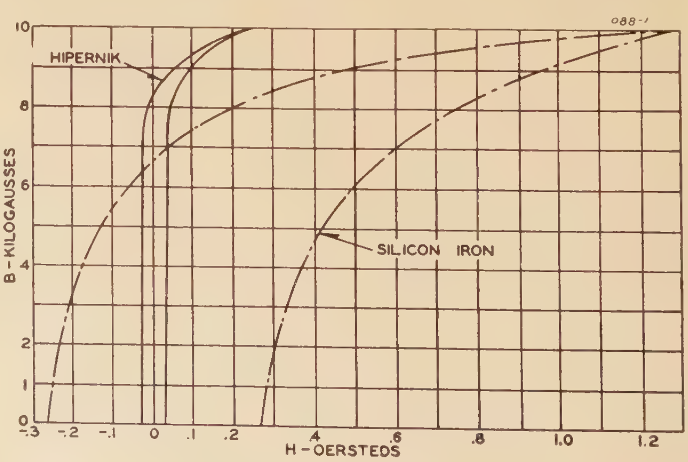


Figure 1. Hysteresis loop for Hipernik and high-silicon iron

Paper 40-88, recommended by the AIEE committee on instruments and measurements, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted July 10, 1939; made available for preprinting April 22, 1940.

PAUL MACGAHAN is development engineer in the meter department of Westinghouse Electric and Manufacturing Company, Newark, N. J.

The author gratefully acknowledges the assistance given in this development by L. J. Lunas and D. A. Young of the Westinghouse meter engineering staff, by Doctor T. D. Yensen of the research department, Westinghouse Electric and Manufacturing Company, and by Doctor H. B. Brooks of the National Bureau of Standards.

1. For all numbered references, see list at end of paper.

Table I. Constants Compared

	(A) Shunted Electrodynamic Wattmeter Without Iron Core	(B) Shunted Iron-Cored Wattmeter
Voltage-coil circuit (460 volts)		
Total resistance (ohms)	13,000	4,350
Resistance, copper coil (ohms)	65	375
Ratio, copper to total resistance	0.005	0.086
Current-coil circuit		
Resistance, current coil (ohms)	0.0055	0.27
Resistance, two shunt leads (ohms)	0.0073	0.12
Resistance, springs (ohms)		0.44
Swamping resistance* (ohms)	0.02	2.12
Total resistance, shunted current circuit (ohms)	0.0328	2.95
Current-circuit copper ratio	0.39	0.17
Full-scale current in coil (amperes)	6.2	0.017
Length, pair of leads (feet)	120.0	120.0
Cross section, leads (square centimeters)	157,380.0	9,700.0
Approximate cost of leads, compared with cost of instrument (per cent)	300	5
Full-load millivolts at shunt (per cent)	200	50
Full-load watts in shunt (10,000 amperes) (per cent)	2,000	500
Temperature influence† (per cent)	1.08	0.4
Weight of moving element (grams)	2.8	1.4
Full-scale torque (millimeter grams)	1.3	1.7
T/W ratio	0.46	1.2
Residual error by reversing polarity of current circuit (per cent)	2.0	0

* Low temperature coefficient wire in series with coil.

† Includes voltage and current circuit and effect of springs.

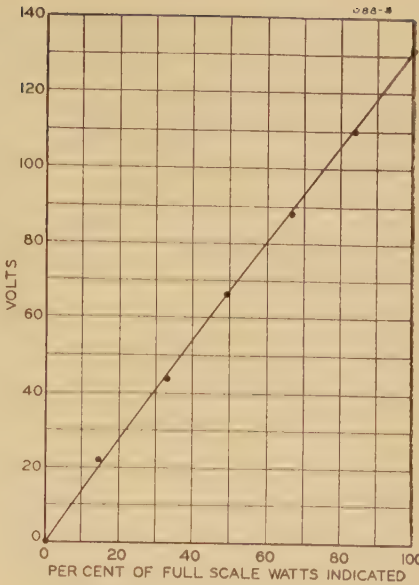


Figure 3. Voltage-error curve

Variable voltage, constant millivolts (amperes); average of increasing and decreasing voltage readings

conventional d-c ammeter, and winding the stationary coils of the electromagnet for excitation from the voltage of the circuit to be measured. This would bring the power-level requirement of the moving-coil circuit down to that of the permanent-magnet moving-coil type, thereby avoiding the difficulties exemplified in column A of table I. The problem of eliminating the residual magnetizing errors due to the usual iron-cored magnetic circuit remained to be solved before a commercially satisfactory instrument could be obtained.

Soon after the original development by Doctor Yensen[4] of the low-loss, low-residual forms of iron known as Hipernik, certain designers succeeded in greatly improving the accuracy of moving-iron ammeters or voltmeters for direct current by using this material for the vanes.

Hipernik is characterized by the almost total absence of magnetic coercive force. As indicated in the hysteresis curve, figure 1, the coercive field is of the low value of 0.04 to 0.06 oersted. As a comparison, the following values may be noted for other forms of steel or iron.

Cold rolled steel, annealed.....2.0 oersteds

Armco (a very pure low-carbon steel)..................1.0 oersted

Silicon steel...........0.32 to 0.85 oersted

In the instrument herein described, use is made of nearly all the usual parts of the corresponding size d-c permanent-magnet moving-coil ammeter, with the exception that an electromagnet is used instead of the permanent magnet. The shape of the electromagnet is so designed as to be assembled in the place of the usual permanent magnet. Hipernik is used for the electromagnet core and also instead of the soft-iron pole pieces and cylindrical core ordinarily used in ammeters or voltmeters. The Hipernik is further annealed in hydrogen at 1,200 degrees centigrade after being machined. The moving element, complete with windings, pointer, springs, and swamping resistance, is exactly the same as that used in the ammeters.

By using the same flux density in the electromagnet as in a permanent magnet, the sensitivity of the current element is made approximately the same as that of the ammeter. This permits the use of the instrument in connection with the usual ammeter shunt, with the same conditions as to length of leads, temperature error compensation, and mechanical action. The ratio of torque to weight, and thus the "figure of merit," is also the same.[5]

The flux density for the working limits of voltage variation in the circuits on which the wattmeter is intended is chosen to correspond with the straightest portion of the magnetization curve of the Hipernik as shown in figure 2. This and the presence of the air gap result in the voltage influence being reduced to a minimum. Figure 3 shows the actual voltage errors of the instrument. The curve is drawn to the average of the ascending and descending values so as to distinguish from the residual errors.

The temperature error of the voltage circuit is reduced to permissible limits by the use of an external resistor of the usual low-temperature-coefficient type such as manganin, constantin, or similar alloy wire.

As in the permanent-magnet moving-coil type, the damping of the instrument is due to the eddy currents generated in the aluminum frame on which the moving coil is wound. As the flux varies with the voltages, the damping effect also varies but is so proportioned as to give the best damping at the average operating voltage. Thus the instrument is inclined to be overdamped at higher voltages and underdamped at low voltages. This, however, is not

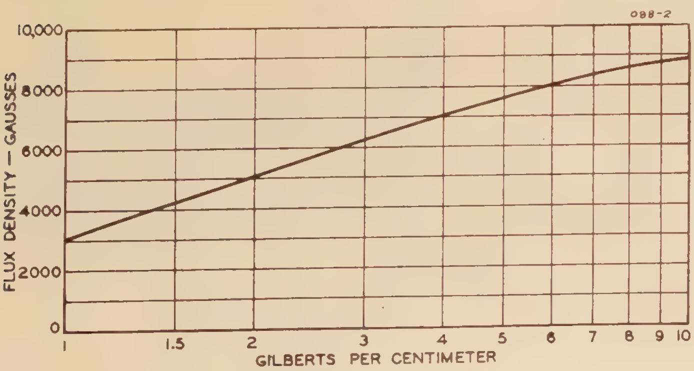


Figure 2. Magnetization curve for Hipernik

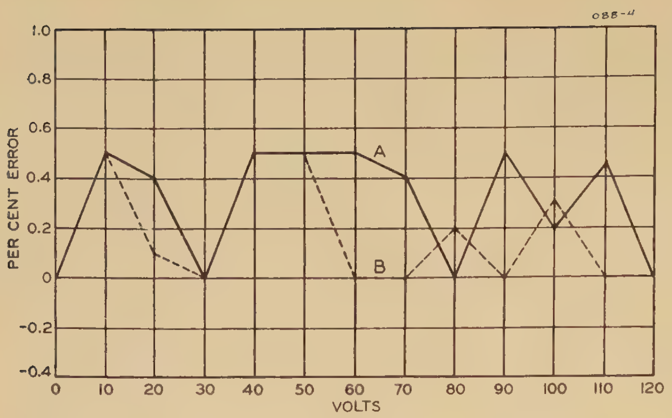


Figure 4. Residual errors—varying voltages, amperes constant

A—Normal polarity
B—Reverse polarity

wholly undesirable, because less damping is required at the lower parts of the scale corresponding in general to lower applied voltage and loads. Where desired, the damping can be increased readily by the well-known method of shunting the entire moving element by a stationary resistance coil. This is, however, at the expense of a corresponding increase of current in the leads which connect the instrument to the shunt.

Figure 4*A* shows the actual residual errors of the instrument on descending values of voltage, the ascending values being used as standard. Figure 4*B* is similar to figure 4*A* except that the polarities have been reversed. It should be noted that there are no residual errors due to variations or reversal of direction of the applied current. Voltage variations are, of course, less extreme in practice than current variations.

A further reduction in the over-all residual error to a value of plus or minus one-fourth per cent is possible by using the average of the increasing and decreasing voltage readings in calibrating the instrument. As errors of this order are less than the usual errors of temperature, friction, and scale marking in the ordinary high-grade switchboard instruments, the residual errors may be disregarded for practical purposes.

The polarity of the voltage does not ordinarily reverse in the course of the normal operation of a wattmeter and the terminals are marked for connection to a definite polarity as used for calibration. This is to avoid the slight additional residual error which would occur from reversal of the electromagnet flux.

It will be noted from the residual-error curve that this effect is not entirely eliminated at all parts of the voltage cycle. However, the performance in this respect compares very favorably with that of the best moving-iron ammeters or voltmeters and is considerably better than in the electrodynamic type described previously.

The completed instrument is shown in figure 5. A similar instrument of the rectangular type, with the scale calibrated in horsepower, is illustrated in figure 6. Figure 7 shows the internal construction of the instrument.

The constants and data of this new d-c wattmeter are given in column *B* of table I. In order to allow a direct comparison

Figure 5. Round-pattern d-c wattmeter calibrated in kilowatts

with the electrodynamic type d-c wattmeter, column *A*, an instrument of the same capacity and for the same length of leads, is tabulated.

While the instrument described in this paper is of the indicating switchboard type, satisfactory d-c recording or portable wattmeters could be built on the same principle.

A further study of the prior art, particularly as practiced in Europe, disclosed the existence of somewhat similar d-c iron-cored wattmeters. In one of the wattmeters described in these European references,[6,7] a magnetic shunt of high-coercive material is permanently applied to the pole pieces of the core of the wattmeter. This shunt is magnetized directly by the field of the voltage coils. As the voltage and main flux varies, a compensating effect results because of the high remanence of the shunting member which produces a remanent flux through the air gap. The strength and polarity of this remanent flux depend upon the previous magnetic condition of the electromagnet. Since this flux is of the opposite polarity to that of the residual magnetization of the core itself, the residual errors are reduced. During the course of development, this construction was tried, but the experiments failed to produce a satisfactory result.

Another form described in the above reference (Keinath, page 284) depends upon the use of a very short magnetic circuit instead of a compensating element, but the performance curves given show considerable residual error, because a nonresidual magnetic material, such as Hipernik was not available.

Application

In general, it is more desirable to indicate the power directly on a dial than to determine the power by simultaneous voltmeter and ammeter readings. This may even be the case where the voltage is fairly constant. But the more important application of the d-c wattmeter is to circuits in which the voltage varies between wide limits, either purposely for speed- or power-control reasons, or because of circuit conditions. The well-known "variable-voltage control," as introduced originally by H. Ward Leonard[2,3] is a typical example.

In this system, the speed of a motor is controlled by varying the voltage across its armature. This is accomplished by changing the field excitation and consequently the voltage of the generator which drives the motor, thus avoiding the losses and other disadvantages of direct rheostatic speed control.

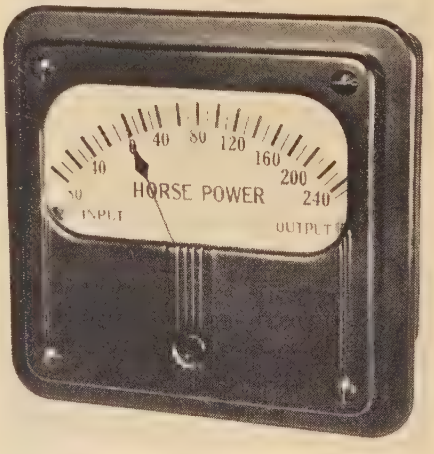


Figure 6. Rectangular-pattern d-c wattmeter calibrated in horsepower

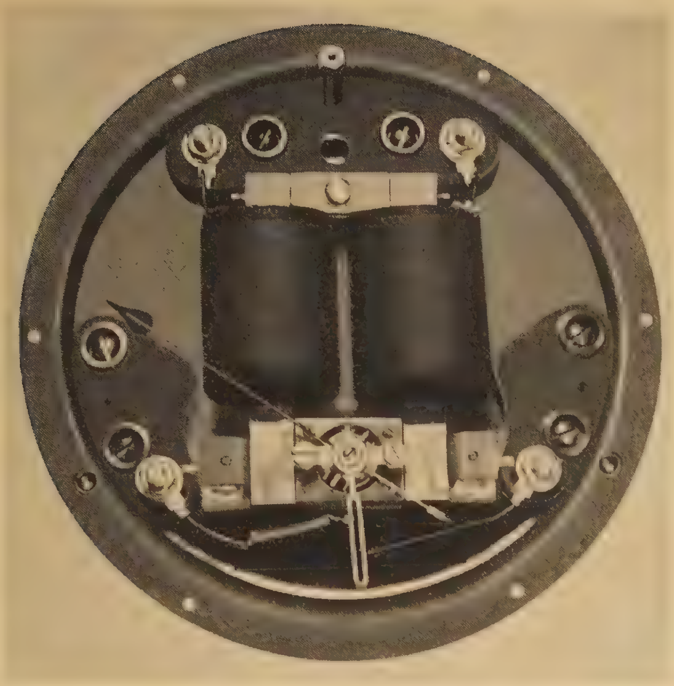


Figure 7. Internal view of d-c wattmeter

When such speed or power control is applied to certain functions, such as harbor dredges or other marine power equipment, it is important to have a direct indication of power at the switchboard or control station.

Another actual application is to power indication of electric dynamometer load sets for production testing of internal-combustion engines. On such applications it is generally preferred to calibrate the scale to read directly in horsepower instead of in kilowatts. The instrument illustrated in figure 6 was specially intended for this purpose.

Bibliography

1. United States Patent 446,489, **Edward Weston.** *Electric World*, November 17, 1889.

2. **H. Ward Leonard,** AIEE Transactions, volume 13, November 18, 1896.

3. **L. W. Markle,** *Electric Journal*, December 1938.

4. Magnetic Properties of the Fifty Per Cent Iron-Nickel Alloy, **T. D. Yensen.** *Journal* of the Franklin Institute, volume 199, 1925, page 333.

Permeability of Hipernik Reaches 167,000, **T. D. Yensen.** *Electric Journal*, volume 28, June 3, 1931, pages 386–8.

Hipernik and Other Iron-Nickel Alloys; Revolutionary Improvements Due to Heat Treating, **T. D. Yensen.** Presented American Society Steel Treating, January 14, 1932. Published in *Metal Progress*, volume 21, June 1932, pages 28–34, 70.

5. Indicating-Instrument Quality, **B. E. Lenehan** and **Paul MacGahan.** *Electric Journal*, volume 26, November 1929, pages 520–3.

J. H. Goss, *General Electric Review*, April 1933.

6. **G. Keinath,** *Die Technik Elektrischer Messgeräte*, volume 1, pages 269–98.

7. *Archiv für Technisches Messgeräte, J-741-I.*

8. **Edgecombe and Ockender,** *Industrial Electrical Instruments*, pages 237–41.

9. Remote Indication of Direct Currents, **F. S. Stickney.** *Electric Journal*, September 1938.

10. United States Patent 1,751,411, **Lamb and Kinnerd.**

11. United States Patent 1,976,498, **Hoare and Parker.**

12. **Drysdale,** *Journal* of IEE, January 1933, page 371.

Discussion

Discussion will be found in the 1941 annual Transactions volume and in the June 1941 Supplement to Electrical Engineering—Transactions Section.

Some Characteristics and Applications of Negative-Glow Lamps

H. M. FERREE
ASSOCIATE AIEE

THE glow lamp is a modern electrical device employing the peculiar properties of various rare gases which when energized by the application of a voltage ionize and pass current. This ionization is accompanied by the production of light.

It has long been known that if sufficiently high voltage is applied to electrodes that are sealed within a bulb containing an inert gas (neon, for example) at the proper pressure, light is produced at the negative electrode or cathode. For this reason, glow lamps are sometimes called "negative-glow lamps" since all the glow takes place at the negative electrode. This is evident on direct current, but on alternating current the reversal of polarity is so rapid that both electrodes appear to glow.

This phenomenon, until recently, was always associated with high voltage. During recent years, however, methods have been developed for so sensitizing electrode surfaces that the voltage for initiating and maintaining a discharge in these rare gases has been reduced to as low as 60 volts on direct current and about 42 volts on alternating current.

Glow Lamps as Light-Producing Devices

With the advent of low-voltage lamps the use of glow lamps on commercial lighting circuits became practical. Various sizes and types of glow lamps are now commercially available ranging from about 0.25 watt to 3 watts in power consumption.

Neon, as used in glow lamps, has proved to be the most efficient of the rare gases as a light-producing medium. In standard commercial glow lamps the light output is about 0.025 candlepower per milliampere. Their normal brightness is approximately 0.8 candlepower per square inch of sensitized electrode surface.

Paper 40-110, recommended by the AIEE committee on production and application of light, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted January 28, 1940; made available for preprinting May 28, 1940.

H. M. FERREE is engineer in the lamp department of the General Electric Company, Cleveland, Ohio.

The author gratefully acknowledges the valuable contributions made by T. E. Foulke.

Since the light output of glow lamps is not great, they of course find only limited use as sources of illumination; they are valuable, however, as signals, pilots, and indicators of the presence of potential and the consequent condition of the device to which this potential is applied.

Why Glow Lamps Are Used

There are many reasons for the selection of glow lamps for innumerable uses. Chief among these reasons are:

1. Low current consumption
2. Insignificant heat
3. Reliability
4. Long life
5. Wide voltage range
6. Ruggedness

The low current consumption is indicated by the current range which is from only 0.002 ampere for the smallest to 0.030 ampere for the largest lamp as now manufactured.

It is apparent that the amount of heat generated at the low wattages that glow lamps consume is insignificant.

These lamps are extremely dependable. Unlike other lamps, they do not suddenly fail at the end of some definite period, but rather, slowly decrease in light output during a period of some 3,000 hours. During this time, slow disintegration causes the walls of the bulb gradually to darken, and this is accompanied by an increasing cathode drop, so that after 3,000 hours use the light output has dropped to 70 per cent of its initial value.

This process continues until the lamp is no longer useful as a light-giving device. Unless the lamps are broken or subjected to a mechanical shock sufficiently violent to short-circuit the electrodes, they will not suddenly fail. This reliability recommends them for many unusual uses.

Voltage

Glow lamps are not affected by voltage variations to the same degree as filament lamps. Their light output varies in almost direct proportion to the current, while life varies, roughly, inversely as the square of the current. It is therefore apparent that ordinary fluctuations experienced on commercial circuits will have but a small influence on either the life or light output.

There are three separate and distinct voltages to be considered when discussing glow lamp voltage, namely:

1. Breakdown
2. Maintaining
3. Supply

Breakdown voltage is that voltage at which the gas becomes ionized and begins to pass current. Below this voltage the lamp cannot be made to light and will not pass current.

Maintaining voltage is the voltage at which the lamp will remain lighted after having started. On alternating current the maintaining voltage is practically the same as the breakdown voltage, while on direct current it is approximately 15 volts lower. There is, therefore, a considerable difference between the supply voltage and that at which the lamp will maintain. This difference is absorbed by a ballast resistor which serves to stabilize the lamp.

Volt-Ampere Characteristics

All gaseous-conduction lamps, of which the glow lamp is one, have a negative or "run away" characteristic. Because of this characteristic, if the lamp were connected directly across a source of voltage sufficiently high to ionize the gas, the current would immediately rise to such proportions as to destroy the lamp. It is

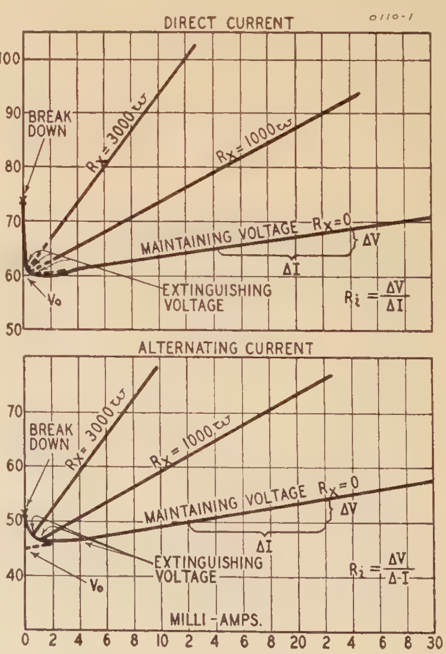


Figure 1. Characteristics of average S-14 two-watt lamp

therefore essential that a limiting resistance be used in series with the lamp. In all lamps referred to here the resistor is built into the base. (See table III.)

The Electrical Characteristics of Negative-Glow Lamps

The negative-glow lamp, when carrying current, can be treated in an electrical circuit as the equivalent of a counter electromotive force with an internal resistance.

Thus for the purpose of calculation, the following symbols can be used:

Let

V = applied voltage
V_0 = the counter electromotive force
R_i = the internal resistance
R_x = the external resistance
I = the current in amperes

Note: R_x = the sum of all resistance outside of the lamp bulb and includes the resistance placed in the base, the resistance of the supply circuit, the meters used in testing, etc.

Then, the current in amperes is:

$$I=\frac{V-V_0}{R_i+R_x}$$

V_0 can accurately be determined from volt-ampere characteristics as the voltage at which the current is reduced to zero, but is approximately given by the minimum maintaining voltage or extinguishing voltage on either alternating current or direct current.

The internal resistance is mainly a function of electrode size, and secondly of the gas composition, pressure, and electrode construction. The exact value can be determined from the quotient of the change in maintaining voltage with corresponding change in discharge current. The a-c internal resistance is somewhat higher than d-c internal resistance, due to the high electrostatic capacity of the discharge in the cathode fall.

Before discharge occurs, that is, at voltages insufficient to cause breakdown, the lamp can be treated as a very high resistance and capacitance.

The Constants of Negative-Glow Lamps

Average values of the constants measured on standard a-c d-c neon glow lamps are included in table I. The external resistance indicated is the value to be used in series with the lamp to secure normal current at the specified alternating voltage. This is the resistance that is placed in lamps based with medium or candelabra screw bases.

A complete characteristic curve is shown and the graphical method of determining the constants of glow devices in figure 1.

Nonresistance Lamps

For some special uses, glow lamps are required without the resistance in the base. Lamps of this type are supplied mounted in double-contact bayonet bases, or bases of such design that they cannot be put into screw sockets, normally used on commercial circuits. With these lamps, it is necessary to use an external series resistor of a value equal to that normally built into the base of the corresponding lamp (see table III), or to operate these lamps in circuits whose natural impedance is sufficient to limit the lamp current to normal values.

Improper application of nonresistance lamps will result in the violent destruction of the lamp.

Glow lamps may be used on voltages many times greater than their normal rating, provided sufficient additional external resistance is used in series with the lamp. The proper value of external resistance to be used with standard lamps on various voltages is shown in table II, together with the proper wattage rating for the resistor. The wattage rating

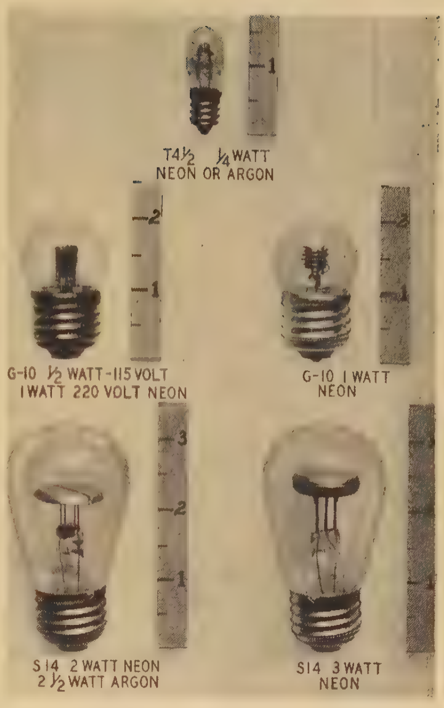


Figure 2

shown is in accordance with accepted practice for cool operation when used in enclosed devices. If used in open circulating air, a rating of approximately one-fourth these wattage ratings may be used.

Example. If a one-quarter-watt 115-volt lamp is to be built into a housing or enclosure, and operated on a 300-volt circuit, the table indicates the use of a 93,000-ohm 1.5-watt resistor. However, if used in open air, a 0.5-watt resistor will suffice.

If lamps having no resistance in the base are operated on any of the voltages indicated in table II, the resistance value shown for a given voltage should be increased by the amount normally used in the base of the corresponding screw-base lamp as shown in table III.

Example. If, in the example given above, a nonresistance lamp were used, the external resistance value should be increased to 123,000 ohms.

Table I

Type Lamp	Supply Voltage	Breakdown Voltage	Minimum Maintaining Voltage	V_0	Ohms R_i	Ohms R_x
S-14-3 watt	120 a-c	53	50	43	310	2,200
	120 d-c	78	58	57	220	2,200
S-14-2 watt	120 a-c	52	49	45	420	3,500
	120 d-c	74	60	60	380	3,500
G-10-1 watt	120 a-c	45	44	43	450	5,900
	120 d-c	65	57	57	400	5,900
T-4½-¼ watt	120 a-c	57	56	44	2,600	30,000
	120 d-c	83	64	63	2,200	30,000
T-2	120 a-c	58	58			200,000
	120 d-c	82	62	60	8,500	200,000

Response Speed

The response speed of neon negative-glow lamps can be explained along three definite lines. First, the ignition or breakdown voltage of glow lamps varies with the duration of voltage application. This is because the discharge has a time lag, and the voltage required for breakdown increases the shorter the duration of application. It is known that the breakdown may increase 50 volts for a time application of 0.01 second and increases further for shorter time intervals.

Table II. External Resistor Values for Use on Various Voltages With Lamps Having Normal Resistance in Base

Line Voltage	150		200		250		300		350		400		450		500	
Lamp	Resistance (Ohms)	Wattage Rating	Resistance (Ohms)	Wattage Rating	Resistance (Ohms)	Wattage Rating	Resistance (Ohms)	Wattage Rating	Resistance (Ohms)	Wattage Rating	Resistance (Ohms)	Wattage Rating	Resistance (Ohms)	Wattage Rating	Resistance (Ohms)	Wattage Rating
*T*4½ 0.25 watt	17,500	0.5	42,000	0.5	68,000	1.0	93,000	1.5	120,000	1.5	150,000	2.0	170,000	2.0	200,000	3.0
*G*10 0.5 watt	9,000	0.5	21,000	1.5	33,000	2.0	45,000	3.0	58,000	3.0	70,000	5.0	82,000	5.0	95,000	5.0
*G*10—220 volts 1 watt							20,000	1.0	32,000	2.0	45,000	3.0	58,000	3.0	70,000	5.0
*G*10—110 volts 1 watt	3,000	1.5	7,000	4.0	11,000	5.0	15,000	10.0	20,000	10.0	24,000	10.0	28,000	20.0	32,000	20.0
S-14 2 watts	2,000	2.0	4,700	5.0	7,500	10.0	10,000	10.0	13,000	20.0	16,000	20.0	19,000	20.0	21,000	20.0
*S*14 3 watts	1,200	3.0	2,800	10.0	4,500	20.0	6,200	20.0	7,800	20.0	9,500	30.0	11,000	30.0	13,000	40.0

Second, the light-current response begins to lose a linear relationship in the neighborhood of 15,000 cycles. For certain uses, however, the current-light response has been used at much higher equivalent frequencies.

Third, after the discharge has been started, the lamp will restart at the maintaining voltage if the current is interrupted for a period not greater than 0.02 second; the normal breakdown is not reached until approximately 0.1 second elapses.

The Influence of Surrounding Light

Practically all glow lamps that start under 90 volts direct current have electrode surfaces so sensitive that they emit electrons photoelectrically when light falls on them. This current emission aids in reducing the breakdown of the lamp. For example, a standard glow lamp measured in the dark had a d-c breakdown of 75 volts and a maintaining voltage of 60 volts; measured in a normally lighted room the breakdown was 73 volts. The same lamp when placed several inches away from a 200-watt incandescent lamp burning at normal voltage broke down at 60 volts. Further increase in illumination did not alter the breakdown, but a sensitive galvanometer placed in the lamp circuit showed current changes with changes in illumination intensity.

Effect of Temperature

Due to the sensitivity of the surface of the electrodes they will emit electrons even at normal room temperatures. When ambient temperatures become as high as 75 to 150 degrees centigrade the breakdown voltage is lowered to some extent. An effect of ambient temperatures of the range of 180 to 200 degrees centigrade is to evolve gases from the glass wall that poison the electrode surfaces. No appreciable effect of temperature can be observed in the range of 0 to 50 degrees centigrade.

The Nature of the Radiation From Glow Lamps

Neon negative-glow lamps radiate mainly in the red and yellow region of the spectrum; there is some radiation from the infrared that is invisible to the eye; a little radiation is spread from the yellow region into the violet. There is very little invisible radiation on the violet side between the violet and the transmission limit of the glass bulbs. The glass bulbs absorb whatever small amount of therapeutic ultraviolet radiation may be generated in the discharge.

Argon glow lamps, which consist of a mixture of gases, radiate mainly in the blue, violet, and near ultraviolet region. The negative glow appears blue-violet. The fact that there is strong radiation in the near ultraviolet region can be demonstrated by the fluorescent effects produced on uranium glass and many phosphorescent and fluorescent substances. The near ultraviolet radiation can be determined by other means too—for example, with a photo-cell, or by photographic means. Here again, the glass container absorbs any ultraviolet of therapeutic value, if it is generated. A recent trial of argon lamps in high-speed photographic printing machines has shown an enormous advantage over all other light sources.

Standard Lamps

A group of glow lamps is now available which covers a wide range of uses and

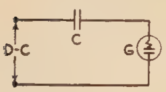


FIGURE 3

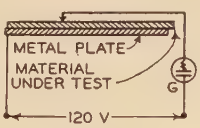


FIGURE 4

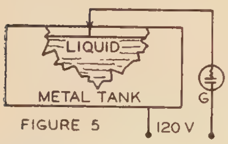


FIGURE 5

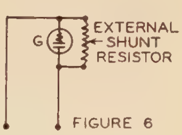


FIGURE 6

Figure 3. A glow lamp as an indicator of short circuits or high-resistance leaks in capacitors

Figure 4. A glow lamp used to test insulating paper, cloth, or other materials

Figure 5. A glow lamp used to check conductivity of liquids

Figure 6. Shunt resistors may be used to regulate the sensitivity of glow lamps

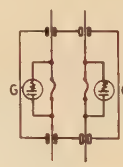


FIGURE 7

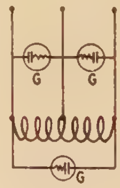


FIGURE 8

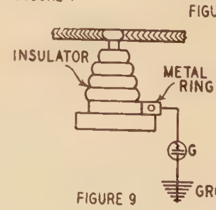


FIGURE 9

Figure 7. When a fuse blows the corresponding glow lamp lights

Figure 8. Serious unbalance is indicated by change in brightness or extinguishing of glow lamp

Figure 9. Capacitively connected to a high-voltage line the glow lamp indicates when line is alive

applications, as shown in figure 2 and the listing of pertinent data in table III.

Applications and Uses

The unique characteristics of the glow lamp lend themselves to many applications and uses which would be quite impossible with devices not possessing these characteristics. Its ability to produce light at low energy levels suggests its use as a signal or pilot in circuits where little current is available or where low current drain is desirable, as in radio circuits, "B"-battery-operated devices, and high-resistance circuits. It may be used in capacitively or inductively coupled circuits where little current may be drawn.

As a Test Lamp

The glow lamp makes an ideal all-around test lamp. It will indicate

1. Circuit alive—circuit continuity
2. By brilliancy, whether 110 or 220 volts
3. By flicker, if 25 cycle
4. Polarity (only negative glows on direct current)
5. Grounded neutral wire. Holding one lead in hand and touching separately each of three legs of a three-wire system with the other lead, the two live lines will cause a glow. Lamp will not light on grounded neutral.

High sensitivity suits the lamp to many high-resistance tests, such as checking leakage in capacitors (figure 3); leakage between tube elements; leaks in insulating material (figure 4); conductivity of liquids (figure 5) and many similar uses.

When the lamp proves to be too sensitive, showing up conditions which may not be particularly serious, the lamp sensitivity may be regulated by shunting a high resistance across it (figure 6).

As a Signal or Pilot Lamp

In many cases the lamp may be permanently connected in a production line or on a machine to indicate the occurrence of certain conditions. It might be used as an indicator of any of the conditions mentioned under the heading "As a Test Lamp".

As a low-current, dependable, long-life pilot lamp, the glow lamp is outstanding and has already been used extensively on all kinds of electrically heated or operated devices, as well as for exit lights, fire-station markers, and location signals for valves, switches, or other emergency control units.

Some further pilot lamp applications are shown in the following sketches:

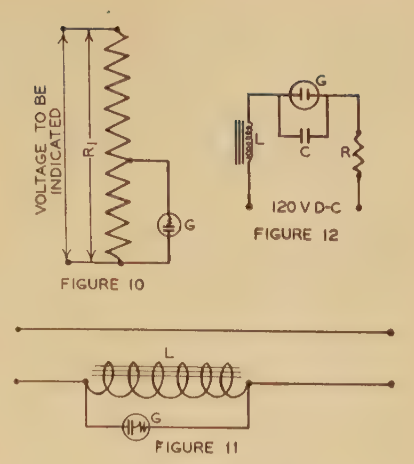
Figure 7. When fuse blows, the respective glow lamp will light.

Figure 8. As a control for polyphase lines. When one phase is overloaded, the respective glow lamp will dim or go out, depending on voltage drop.

Figure 9. To indicate that high-voltage lines are carrying current. The small capacity current will cause lamp to glow.

Figure 10. As a visual voltmeter. When desired voltage develops across R_1 the voltage across the lamp rises to the breakdown value causing it to light.

Many other adaptations may be made of the critical breakdown voltage of the glow lamp by connecting it across resistors, chokes, or current transformers so chosen that the normal drop across the lamp is below breakdown. Then, any condition which causes the voltage to reach the breakdown value will be indicated by a glow in the lamp. (Figure 11.)



Figures 10–12

As a Low-Frequency Generator

If a glow lamp is shunted across a capacitance and connected through a resistance to a d-c supply, the capacitor will charge up to the breakdown voltage and discharge through the lamp. By proper selection of the circuit constants, the lamp may be made to flash or in fact to oscillate at frequencies well up into the audio range. (Figure 12.) The addition of choke L_1 insures uniformity of oscillation and may vary from 1 to 30 henrys.

References

1. Gaseous Conduction Light From Low-Voltage Circuits, Moore. AIEE Transactions, volume 39, 1920, page 732.

2. Some Electrical Properties of Neon Lamps, Pearson and Anson. P.S.L. *Proc.*, volume 34, 1922, page 175.

Table III. Standard Glow Lamps

Watts	Volts	Starting Volts Below Minimum Marking on Base: A-C	Starting Volts Below Minimum Marking on Base: D-C	Current Rating Amperes at 120 Volts	Approx. Resistance in Base Ohms*	Bulb	Finish†	Screw Base	Service‡	Useful Life Hours at 120 Volts	Electrode Shape	Gas	Over-all Length (Inches)
3	115–125	60	25	0.030	2,200	*S*-14	Clear	Medium#	A-c d-c	3,000	Round plates	Neon	3 9/32
2	115–125	60	25	0.020	3,500	*S*-14	Clear	Medium#	A-c d-c	3,000	Half round plates	Neon	3 9/32
2	115–125	60	25	0.020	3,500	*S*-14	Sprayed red or yellow	Medium#	A-c d-c	3,000	Half round plates	Neon	3 9/32
2 1/2	115–125	60	25	0.025	2,500	*S*-14	Clear only	Medium#	A-c d-c	3,000	Half round plates	Argon	3 9/32
1/2**	115–125	20		0.005	3,500	*G*-10	Clear	Medium#	A-c only	3,000	Cylinder	Neon	1 63/64
1	115–125	60	25	0.010	4,800	*G*-10	Clear	Medium#	A-c d-c	3,000	Cylinder and helix	Neon	1 63/64
1/4	115–125	60	25	0.002	30,000	*T*-4 1/2	Clear only	Candelabra	A-c d-c	3,000	Hemisphere	Neon	1 1/2
1/4	115–125	40		0.003	20,000	*T*-4 1/2	Clear only	Candelabra	A-c only	1,000	Hemisphere	Argon	1 1/2

* Lamps supplied without resistance only when equipped with double-contact bayonet base.

† Lamps listed in clear finish are available with sprayed red or yellow finish, except in the one-fourth-watt sizes.

‡ On direct current, only one electrode (negative) glows, but gives same candlepower as do both electrodes on alternating current.

** Supplied in one-watt size for 210–240-volt a-c or d-c service, medium screw base only.

Available in skirted candelabra screw base.

Note: Normal light output is obtained at voltage range shown. Lamps will operate at reduced light output down to starting voltage shown.

An Improved A-C Pilot-Wire Relay

J. H. NEHER
MEMBER AIEE

A. J. McCONNELL
ASSOCIATE AIEE

DESPITE the fact that it is quite generally conceded that differential protection is the most desirable principle for line protection, yet few applications of relay systems of this type have been made until recently except for lines of very short length. The older forms of pilot-wire differential protection required three or four wires of low resistance; and even then, the systems were characterized by lack of sensitivity, and by high burden on the current transformers.

Because of the general availability of reliable communication facilities between power stations, d-c pilot-wire systems,[1] utilizing a single pair of telephone-type pilot wires, have been developed. These systems operate on the "directional comparison" principle, hence require a potential supply for the relays, and may be influenced by out-of-step conditions. The relays ordinarily used are not easily insulated to protect against induced voltages. While the requirement for a potential supply, the tendency to operate on out-of-step conditions, and the matter of relay insulation are not always influencing factors in the choice of a relay system, there are, of course, advantages in the use of a system which would not be so limited.

A differential system which uses a single telephone pair as a pilot circuit is definitely limited by the energy which can be transmitted over the pilot wires. This energy limit is far below that required by the older forms of differential protection; and some means must be found for making the single relay system operative on all types of faults. Such a relay system has been developed[2] in which these difficulties have been solved by the use of supersensitive relay elements and networks.

This paper describes a similar relay system in which one standard relay element is used at each terminal. It is operative over a single telephone pair and gives full protection for any type of fault without the need for a potential supply. In addition, there is adequate insulation between the relay element and the pilot wires. The relay is of the current product type, in which the energy required to operate the element is provided largely by the polarizing current; thus permitting the use of a relatively low energy level in the pilot-wire circuit.

In many respects this system is similar to the "Translay" system[3,4] used successfully in Europe for many years. Of its several improvements, an outstanding one is the use of the modern high-speed induction-cylinder relay element.

Basic Principles of the Pilot-Wire System

Fundamentally, the system is of the opposed-voltage type in which substantially no current flows in the pilot wires under normal, or through fault conditions.

Figure 1 shows the fundamental circuits on a single-phase basis. At each end of the line, the current transformer energizes the following two elements:

1. The polarizing coils of a wattmetric type of relay element.
2. The primary of the "input transformer", which is a reactor with a secondary winding.

Current flow in the primary of the input transformer causes a voltage to be induced in the secondary. This voltage is applied to a shunt-connected restraining circuit, and to the operating circuit which is in series with one of the pilot wires.

The current which flows in the restraining coil of the relay reacts with the polarizing coil current to produce a torque in the contact-opening direction.

The current which flows in the operating-coil circuit is dependent upon the voltages of the input transformers at both ends of the line. Under normal or through fault conditions, these voltages oppose each other, and practically no

A—Input transformer
B—Current polarizing coils
C—Restraining coil
D—Operating coils
E—Contacts
F—Pilot wires

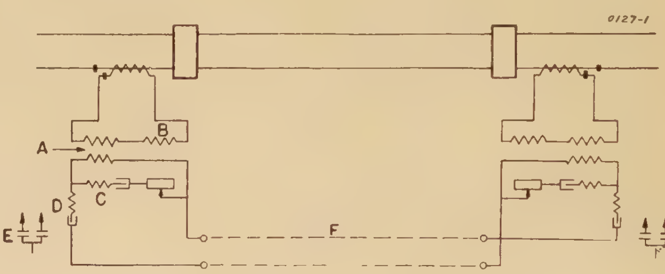


Figure 1. Single-phase schematic diagram of relay circuits

Paper 40-127, recommended by the AIEE committee on protective devices, and presented at the AIEE Pacific Coast convention, Los Angeles, Calif., August 27–30, 1940. Manuscript submitted June 20, 1940; made available for preprinting July 11, 1940.

J. H. NEHER is senior engineer in charge of relay design, Philadelphia Electric Company, Philadelphia, Pa.; A. J. MCCONNELL is design engineer, General Electric Company, Philadelphia, Pa.

1. For all numbered references see list at end of paper.

3. NEON GLOW DISCHARGE LAMPS ON D.C., McGregor, Morris, Dowty, and Privett. *Anne d. Phys.*, 1922, page 625.

4. NEON GLOW DISCHARGE LAMPS ON A.C., Brockbank and Ryall. *Electrician*, volume 90, 1923, page 4.

5. PEAK VOLTAGE MEASUREMENTS BY MEANS OF NEON GLOW LAMPS, L. E. Ryall. *World Power* (England), May 1924.

6. DIFFUSION OF IONS IN NEON TUBES, Foulke and McCurdy. *Phys. Rev.*, volume 23, 1924, page 776.

7. EXPONENTIAL RISE OF DISCHARGE CURRENTS IN NEON, Foulke and McCurdy. *Phys. Rev.*, volume 23, 1924, page 776.

8. A VISUAL WARNING SIGNAL FOR THE ROENTGENOSCOPIC ROOM, F. W. Bishop. *Am. Journal of Roentgenology and Radium Therapy*, volume 23, 1930, number 3.

9. ALTE UND NEUE GLIMMLAMPENFORMEN, W. Pohle and H. Straehler. *Osram*, volume 5, 1935, number 8–9.

10. ANWENDUNGS-MÖGLICHEITEN DER GLIMMLAMPE, Doctor Hans Ewest. *Osram*, Berlin, 1935.

11. A COLD CATHODE ARC DISCHARGE TUBE, Germeshausen and Edgerton. ELECTRICAL ENGINEERING, volume 55, 1936, page 790.

12. A NEW TYPE VOLUME INDICATOR, S. Read, Jr. *Jour.* S.M.P.E., April 1936.

13. VACUUM TUBES IMPROVE SELECTIVE RINGING, L. J. Stacy. *Bell Lab. Record*, volume 15, number 4, 1936, page 111.

14. COLD CATHODE GAS FILLED TUBES AS CIRCUIT ELEMENTS, S. B. Ingram. ELECTRICAL ENGINEERING, July 1939, page 342.

15. ON ELECTRONIC VOLTAGE STABILIZERS, Hunt and Hickman. *Rev. Sci. Inst.*, January 1939.

Discussion

Discussion will be found in the 1941 annual TRANSACTIONS volume and in the June 1941 SUPPLEMENT to ELECTRICAL ENGINEERING—TRANSACTIONS SECTION.

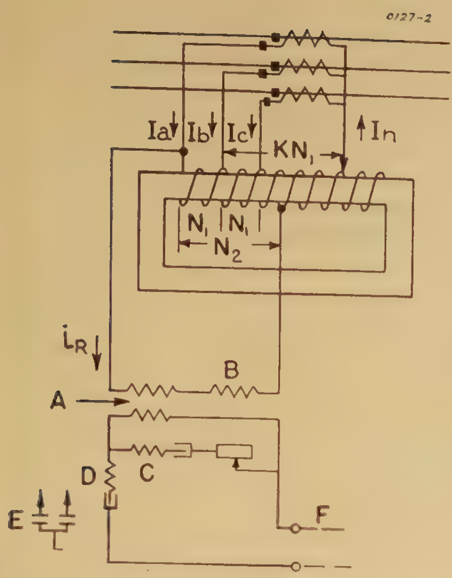


Figure 2. Schematic diagram of one termina showing connections of autotransformer

A, B, etc., same as figure 1

current flows in the pilot wires. With an internal fault, the voltages are additive; and the resultant current flowing in the operating circuit reacts with the polarizing current, and produces a torque in the contact-closing direction of sufficient magnitude to overcome the restraining torque. On an internal fault, the pilot-wire current is proportional to the sum of the fault currents entering each end.

The wattmetric type of element used is of the multipole induction-cylinder construction which has previously been described before the AIEE.[5] Three of the potential coils are used in the operating circuit, and the fourth furnishes the restraint. The four current polarizing coils are connected in series.

Purpose of Capacitors in Operating and Restraining Circuits

Since the torque of a wattmetric type of relay is proportional to the product of two currents and the sine of the angle between them, maximum torque occurs when the two currents are displaced by 90 degrees. The secondary voltage of the input transformer is displaced by 90 degrees from the current in the primary. Thus, for maximum torque, the currents flowing in the operating circuits must be in phase with the voltages producing them. For this purpose, capacitors are used in both the restraining and operating circuits; both circuits being resonant at rated frequency.

Besides producing a high-efficiency relay, other beneficial effects are obtained from the resonant operating circuit. The current which flows in the operating circuit, because of the electrostatic capacity of the pilot wires, is highly leading; and therefore, is almost in phase with the polarizing current. In consequence, substantially no operating torque is produced by pilot-wire capacity current. Hence, greater sensitivity is possible without interference by capacity current. The resonant circuit suppresses harmonic currents in the pilot wires; especially the higher noise-producing harmonics. Also, the effect of currents caused by switching transients is greatly reduced, since such currents usually contain a variety of harmonics. Thus, the pilot circuit is both free from outside interference, and at the same time, does not itself produce troublesome telephone interference. Since differences in current transformers usually involve a phase-angle shift as well as a change in the ratio, the voltages applied to the pilot wires may be out-of-phase during an external fault. However, the circulating current which flows through the pilot wires because of phase shift is at an angle unfavorable to the development of full relay torque.

Purpose of the Wattmetric Type of Relay Element

Since the operating torque of the relay element depends upon both the polarizing and the pilot-wire currents, most of the driving energy of the relay can be concentrated in the polarizing coils, thus making it possible to obtain a satisfactory torque level with a small amount of power transmitted over the pilot wires. Thus, special pilot wires of extremely low resistance are not required.

Open and Short-Circuited Pilot Wires

This pilot-wire system is subject to the disadvantage common to all pilot-wire systems, namely, incorrect operation when the pilot wires are either open-circuited or short-circuited. An open-circuited pilot wire will prevent tripping on an internal fault; whereas short-circuited pilot wires will cause tripping on external faults.

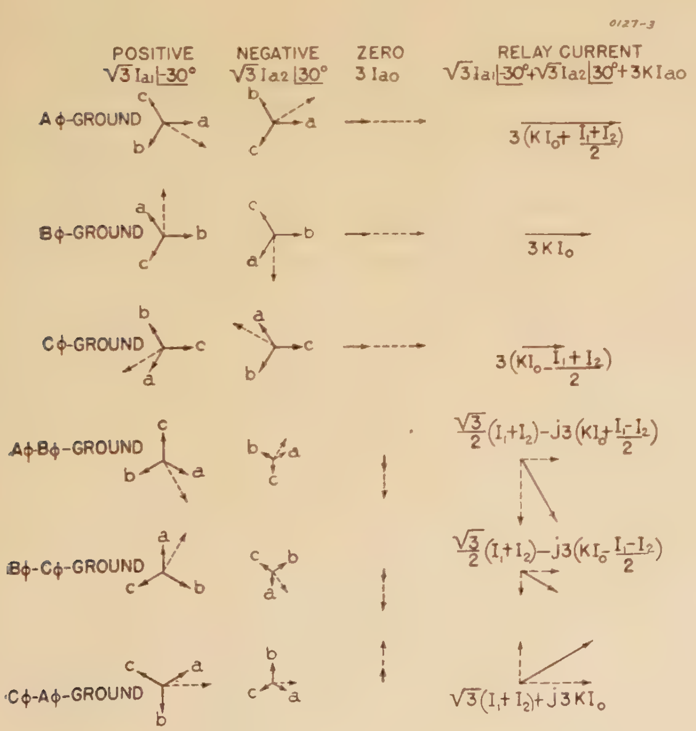
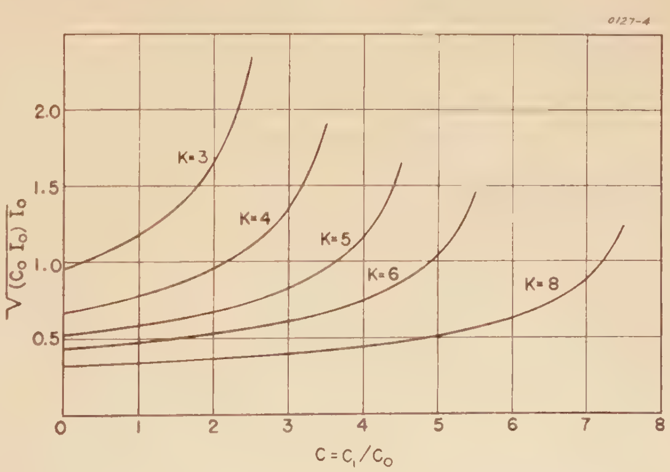


Figure 3. Vector diagrams of relay currents

Figure 4. Pickup current on phase C-ground fault (zero pilot-wire resistance)

Method of Obtaining Polyphase Protection

Thus far, the pilot-wire relay system has been considered on a single-phase basis only, in order to show that it operates in response to circulating current



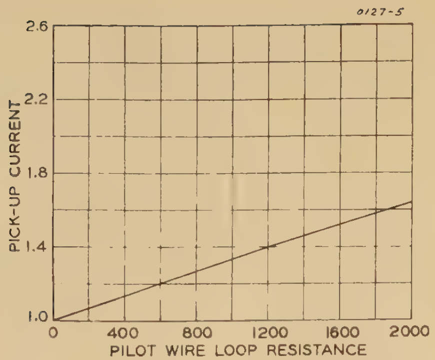


Figure 5. Effect of pilot-wire resistance on pickup current

Pickup current plotted as multiple of pickup current with zero pilot-wire resistance

in the pilot wires reacting with the polarizing current. In order that a single pair of relays can furnish protection for all phase and ground faults over a single pair of pilot wires, it is necessary to provide some means of impressing on the relay system a single electrical quantity for any type of fault.

It is often true that the simplest device also provides the most satisfactory performance. In this instance, a simple tapped autotransformer is the means of providing the single electrical quantity.

Figure 2 shows the connections to and from the autotransformer. The autotransformer is interposed between the current transformers and the remaining relay circuits. Considering the two left-hand sections of the autotransformer, it is obvious that its output, during phase faults, is proportional to $(I_a - I_c)$. During ground faults the residual current flows through the right-hand section, producing a component of output current which is proportional to I_n times factor K. K is a constant relating the turns in the phase and ground windings, and is adjustable by means of taps. The total output current of the autotransformer is therefore proportional to $I_a - I_c + KI_n$ (equation 3, appendix I).

Figure 3 shows vectorially the relations between positive, negative, and zero-phase-sequence currents, and the output current of the autotransformer on faults involving ground.

Blind Spots

When a pilot-wire relay system utilizes any network to obtain a single-phase output current from a three-phase source, there is always the danger that the relays at both ends of the line may fail to operate under certain internal fault conditions, even though the fault current is apparently of sufficient magnitude to exceed the relay pickup. Such conditions may be termed "blind spots". Any such relay system must be carefully analyzed to determine its limitations in this respect. In general, "blind spots" are possible only on faults involving ground.

With the relay system described above, one of the following conditions is necessary for a "blind spot" to occur:

1. A low autotransformer output current at *each* end of the line.
2. A low pilot-wire current.
3. An unfavorable phase angle between the pilot-wire and polarizing currents at *each* end of the line.

It is possible (although usually avoidable by properly selecting constant K) to have a low autotransformer output at one end of the line. However, with a solidly grounded neutral system, it is not possible to have a low autotransformer output at each end of the line simultaneously; nor are any of the other conditions possible.

In unusual instances, it may not be possible to avoid a low polarizing current at one end of the line. The relay at the other end of the line will operate, however, and after the circuit breaker at that end opens, the relay at the first end will operate sequentially, provided, of course, that there is sufficient current for operation on single-end-feed.

A low autotransformer output current at one end is caused by unequal distribution of positive and zero-phase-sequence currents. For example, it can be seen (figure 2) that with a C phase-ground fault, the current in phase C can divide in such a manner that I_n will flow in one direction, and the remainder of the current in phase C will flow in the opposite direction. (See also equation 29, appendix II.) The C phase-ground fault is the limiting condition in this respect (appendix II), and figure 4 provides a ready means for selecting the constant K in order to insure adequate torque for simultaneous relay operation with a C phase-ground fault. These curves show the relay pickup in terms of the geometric mean $(\sqrt{(c_0I_0)(I_0)})$ of the zero-phase-sequence current fed from one end (c_0I_0), and the total zero-phase-sequence current (I_0), for various values of K and $c=c_1/c_0$, where c_1 and c_0 are positive and zero-phase-sequence distribution factors, respectively.

In those cases in which it is apparently impossible to avoid sequential tripping, it is sometimes possible to eliminate the cascading of circuit breaker times by a simple arrangement whereby the operation of either pilot-wire relay immediately short-circuits the pilot-wire circuit at its end of the line. To the second relay, the fault then appears to be similar to a single-end-feed condition.

With an overhead system, the neutral points of which are all resistance grounded, it is theoretically possible for the relays at one or both ends to develop insufficient or negative torque on a C phase-A phase-ground fault. This can be noted from equation 35 given in appendix II. The large number of variables in this equation prevents a simple treatment such as has been given above in the case of a single-phase-to-ground fault. A study of this equation indicates, in general, that if simultaneous operation is obtained at both ends on all phase-to-phase faults, sufficient torque will be available to operate both relays under any practical case of resistance grounding, although sometimes the operation may be sequential.

Table I. Minimum Operating Currents

Type of Fault	Phases	CT Secondary Pick-Up Amperes
Three-phase	A-B-C	4
Phase-to-phase	A-B and B-C	7
Phase-to-phase	A-C	3.5
Single-phase-to-ground	C-ground**	1.0 to 3.5*

* Five taps to adjust for constant K.

** Pick-ups slightly less on phases A and B.

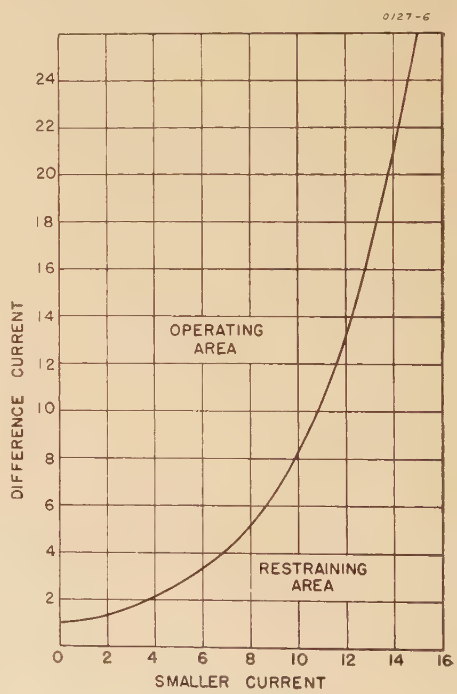


Figure 6. Operating-restraining characteristics on through faults (currents in phase)

Plotted as multiples of single-end-feed pickup current

Characteristics of the Relay System

Minimum Operating Current

Based on single-end-feed, table I gives the minimum operating currents on various types of faults. These values are based on zero pilot-wire resistance. Since the operating coil current decreases as the pilot-wire resistance increases, the pickup current will increase. The effect of pilot-wire resistance upon pickup is shown in figure 5.

Operating-Restraining Characteristics

If saturation of the mixing transformers could be neglected, the slope of the operating-restraining curve on a through fault would be approximately 50 per cent; that is, differential current in per cent of the smaller of the restraining currents. However, saturation of the mixing transformer causes the slope to increase rapidly at the higher currents as shown in figure 6.

This characteristic permits the use of unmatched current transformers or burdens. Since the operating current varies with the resistance of the pilot wire, means are provided to adjust the restraining current so that substantially the same curve applies regardless of the pilot-wire resistance.

Current Transformer Burden

The three-phase burden is less than one volt-ampere per phase at five amperes. The single-phase-to-ground burden varies between 12 and 57 volt-amperes at five amperes, depending upon the ground tap (constant K) used.

Operating Time

The time-current curve is shown in figure 7. This curve is based upon single-end-feed. Operating times are slightly less when additional operating current is received over the pilot wires from the other end of the line.

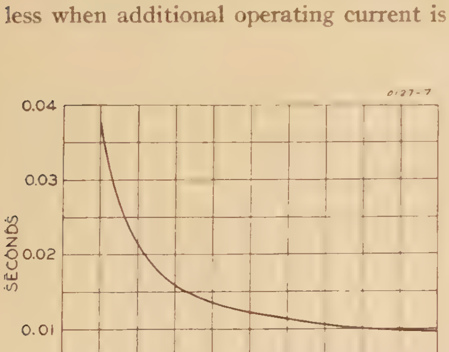
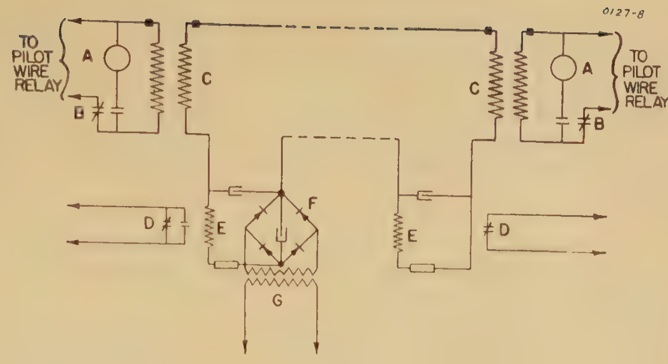


Figure 7. Operating time

Current plotted as multiple of minimum pickup with single-end-feed

Figure 8. Schematic diagram of automatic supervisory equipment

A—Voltmeter
B—Switch
C—Insulating transformer
D—Contacts
E—Relay coil
F—Rectifier
G—Supply transformer



Pilot-Wire Circuit

The reliability of any pilot-wire protective scheme is dependent upon continuity of the pilot channel. Interruptions may occur from electrical and mechanical causes which include the following:

1. Induction from power lines.
2. Difference in station ground potentials.
3. Lightning.
4. Contact with foreign objects.
5. Unauthorized tampering with pilot circuits.

Experience has indicated that the use of lead-sheath cable of sufficient insulation and mechanical strength practically eliminates trouble from the first four hazards. Elimination of interruptions caused by trouble-shooting, etc., can be accomplished by treating the pilot-wire circuit as any high-voltage power circuit, thus requiring clearance orders from the dispatcher. If the circuits are leased, coordination is necessary between the lessee and lessor.

Insulation stress caused by induction can be reduced by the use of different routes for the power lines and pilot cable.

The difference between station ground potentials is largely concentrated near the power station. If this potential difference is large, it may be economical to use two different levels of cable insulation strength, using the higher level close to the stations. In such instances, neutralizing transformers[6] can also be considered.

Whether the voltage is derived from induction, or rise in station ground potential, each relay is protected by means of an insulating transformer tested at over 10,000 volts between the pilot-wire winding and ground, and between the pilot-wire winding and the relay winding.

In addition to insulation problems, induction may be the cause of further difficulty, namely, incorrect operation because of a voltage difference between the pilot wires. If the pilot-wire circuit is the preferred twisted pair, this voltage difference does not have to be considered. However, if the pilot wire circuit is other than a twisted pair, it should be determined that the voltage between wires is less than five volts under maximum fault conditions.

Pilot-Wire Supervision

Since the pilot wires are such an important part of the relay system, manual pilot-wire checking equipment is furnished with each relay. The equipment consists of a voltmeter and a switch (*A* and *B* in figure 8). When the switch is operated, the voltage transmitted from the relay at the opposite end of the pilot wires is read. A positive reading indicates a sound operating circuit including both insulating transformers and the relay at the other end of the line. A zero voltage reading indicates a short circuit or open circuit, provided, of course, there is sufficient load current to produce a voltmeter deflection.

Voltmeter readings taken at the same time as the usual periodic readings should provide an ample check of the pilot circuit. However, some operators may desire a continuous automatic check of the pilot wires. The automatic supervisory equipment is shown schematically in figure 8. A small direct current is circulated continuously over the pilot wires. Sensitive polarized relays at each end indicate a short-circuited or an open-circuited pilot channel, and close alarm circuits at each station. The source of direct current is a rectifier supplied from a small transformer. Each relay is tested at 10,000 volts between the pilot-wire circuit and both low-voltage circuits, and between the pilot-wire circuit and the relay case.

Conclusion

In conclusion, it is felt that the relay system described, offering protection

against all types of faults, and consisting of a relatively simple arrangement of standard components, constitutes a definite step toward meeting the requirements of the ideal relay scheme.[7]

Appendix I

Operation of the Mixing Autotransformer

From figure 2 it is evident that the ampere-turn balance in the mixing autotransformer will always be as follows:

$$N_2 i_R = N_1[I_a(1+K)+I_bK+I_c(K-1)] \quad (1)$$

Since

$$I_n = I_a+I_b+I_c \quad (2)$$

$$I_R = I_a-I_c+KI_n \quad (3)$$

where

$$I_R = \frac{N_2}{N_1} i_R \quad (4)$$

is the current fed to the relay element, referred to the input side of the mixing autotransformer.

Equation 3 may be resolved into its phase-sequence components as follows:

$$I_a = I_{a1}+I_{a2}+I_{a0} \quad (5)$$

$$I_c = I_{c1}+I_{c2}+I_{c0} = I_{a1}\underline{/120^\circ}+I_{a2}\underline{/-120^\circ}+I_{a0} \quad (6)$$

$$I_n = 3I_{a0} \quad (7)$$

$$I_R = \sqrt{3}I_{a1}\underline{/-30^\circ}+\sqrt{3}I_{a2}\underline{/30^\circ}+3KI_{a0} \quad (8)$$

The derivation of the currents fed to the relay elements under the various fault conditions will be made on the assumption that the positive and negative-phase-sequence networks are identical, and that the positive and zero-phase-sequence networks have the same phase angle, except as noted hereafter.

The resultant relay currents for all types of faults will be expressed in terms of three fundamental currents

$$I_P = \frac{\sqrt{3}E}{2Z_1} \quad (9)$$

which is the total phase-to-phase fault current

$$I_N = \frac{3E}{2Z_1+Z_0} \quad (10)$$

which is the total ground current for a single-phase-to-ground fault, or

$$I_{N'} = \frac{3E}{Z_1+2Z_0} \quad (11)$$

which is the corresponding total ground current on a two-phase-to-ground fault. In equations 9, 10, and 11, the voltage, currents, and impedances can be considered to be scalar quantities, since it has been assumed that Z_1 and Z_0 have the same phase angle.

The following expressions for the resultant relay currents on faults not involving ground are self-evident from equation 3. (C_1 and C_0 are the current distribution factors for the positive and zero-phase-sequence networks, respectively.)

(*a*). Three-phase and *C* phase-*A* phase faults

$$I_R+2c_1I_P \quad (12)$$

(*b*). *A* phase-*B* phase and *B* phase-*C* phase faults

$$I_R = c_1I_P \quad (13)$$

The derivation of the relay current on faults involving ground can best be made from equation 8 and the vector diagram shown in figure 3.

(*c*). *A* phase-ground fault

$$I_R = (Kc_0+c_1)I_N \quad (14)$$

(*d*). *B* phase-ground fault

$$I_R = Kc_0I_N \quad (15)$$

(*e*). *C* phase-ground fault

$$I_R = (Kc_0-c_1)I_N \quad (16)$$

In the case of two-phase-to-ground faults the following relationships have been employed which are justifiable in view of the assumption that $Z_2=Z_1$. Here again, I_1 and I_2 are scalar quantities, and are the magnitudes of I_{a1} and I_{a2}, respectively.

$$I_1+I_2 = \frac{(Z_1+Z_0)E}{Z_1(Z_1+2Z_0)}+\frac{Z_0E}{Z_1(Z_1+2Z_0)} = \frac{E}{Z_1} \quad (17)$$

$$I_1-I_2 = \frac{E}{Z_1+2Z_0} \quad (18)$$

(*f*). *A* phase-*B* phase-ground fault

$$I_R = c_1I_P-j(Kc_0+c_1/2)I_{N'} \quad (19)$$

(*g*). *B* phase-*C* phase-ground fault

$$I_R = c_1I_P-j(Kc_0-c_1/2)I_{N'} \quad (20)$$

(*h*). *C* phase-*A* phase-ground fault

$$I_R = 2c_1I_P+jKc_0I_{N'} \quad (21)$$

Appendix II

Relay Torque Equations

From figure 1 and the discussion given in the text it is apparent that the torque developed by the relay in terms of the pick-up torque t can be expressed as:

$$T = \frac{I_R}{t}\left(\frac{N_1}{N_2}\right)^2 k\left[\frac{I_R-I_{R'}\cos\theta}{2R_o+R_p}-\frac{I_R}{3R_r}\right] \quad (22)$$

where

I_R = the current fed to the relay element at the end under consideration

$I_{R'}$ = the current fed to the relay element at the other end

θ = the phase angle between $I_{R'}$ and I_R

k = transreactance of the pilot-wire input transformers

R_o = resistance of relay operating circuit

R_r = resistance of relay restraint circuit

R_p = resistance of pilot-wire loop

With the restraint circuit properly adjusted for 50 per cent slope, equation 22 becomes, with the proper values substituted:

$$T = \frac{I_R}{32.5F}[I_R-I_{R'}\cos\theta-I_R/3] \quad (23)$$

where the effect of the pilot-wire resistance is given by

$$F = 1+\frac{R_p}{1{,}140} \quad (24)$$

By the use of equation 9 through 16, and 19 through 21, equation 23 may be solved to give the torque developed on internal faults ($\theta=180$ degrees) for the various phase and ground combinations. The expressions for pilot-wire currents $(I_R+I_{R'})$ are similar to the corresponding expressions for I_R with c_1 and c_0 made unity where they occur.

When I_R and $(I_R+I_{R'})$ have reactive components no torque can result from the cross-product terms.

(*a*). Three-phase and *C* phase-*A* phase faults

$$T = 4\frac{I_P^2}{32.5F}c_1(1-c_1/3) \quad (25)$$

(*b*). *A* phase-*B* phase and *B* phase-*C* phase faults

$$T = \frac{I_P^2}{32.5F}c_1(1-c_1/3) \quad (26)$$

(*c*). *A* phase-ground fault

$$T = \frac{I_N^2}{32.5F}(Kc_0+c_1)[K+1-(1/3)(Kc_0+c_1)] \quad (27)$$

(*d*). *B* phase-ground fault

$$T = \frac{I_N^2}{32.5F}Kc_0(K-Kc_0/3) \quad (28)$$

(*e*). *C* phase-ground fault

$$T = \frac{I_N^2}{32.5F}(Kc_0-c_1)[K-1-(1/3)(Kc_0-c_1)] \quad (29)$$

It is apparent here that reduced or negative torque can be obtained, depending upon the relative values of Kc_0 and c_1. Equation 29 can be rewritten in the following form:

$$T = \frac{I_N^2}{32.5F}c_0(1-c_0/3)\left[K\left(K-\frac{3-c_1}{3-c_0}\right)-\frac{c_1}{c_0}\left(K-\frac{3-c_1}{3-c_0}\right)\right] \quad (30)$$

in which the solution of the expression contained within the brackets forms the basis of figure 4 discussed in the text.

(*f*). *A* phase-*B* phase-ground fault

$$T = \frac{I_P^2}{32.5F}c_1(1-c_1/3)+\frac{1}{4}\frac{I_{N'}^2}{32.5F}(2Kc_0+c_1)\times[2K+1-(1/3)(2Kc_0+c_1)] \quad (31)$$

(*g*). *B* phase-*C* phase-ground fault

$$T = \frac{I_P^2}{32.5F}c_1(1-c_1/3)+\frac{1}{4}\frac{I_{N'}^2}{32.5F}(2Kc_0-c_1)\times[2K-1-(1/3)(2Kc_0-c_1)] \quad (32)$$

Here again, it is possible that a negative torque from the second half of equation 32

will offset the positive torque of the first part of the equation. It is apparent, however, that the relationships between Kc_0 and c_1 required to render equation 29 positive will also make the second part of equation 32 positive.

(h). C phase-A phase-ground fault

$$T=4\frac{I_P^2}{32.5F}c_1(1-c_1/3)+\frac{I_{N'}^2}{32.5F}Kc_0(K-Kc_0/3) \quad (33)$$

In the case of a two-phase-to-ground fault with the system grounded through a resistance, the previous assumption that Z_1 and Z_0 have the same phase angles is no longer valid. The introduction of an additional resistance component in Z_0 will advance the components containing $I_{N'}$ in phase position. This will increase the values of torque developed from equations 31 and 32 but may decrease it in the case of equation 33.

Although equation 21 was derived on the basis that I_P and $I_{N'}$ were scalar quantities, it can be shown that the equation is also valid when I_P and $I_{N'}$ are vectors. If the resistive and reactive components of Z_1 and Z_0 are R_1, X_1 and R_0, X_0 respectively, then the angle of advance of $I_{N'}$ is given by the following expression

$$\phi=\tan^{-1}\frac{X_1}{R_1}-\tan^{-1}\frac{X_1+2X_0}{R_1+2R_0} \quad (34)$$

Equation 21 in appendix I becomes

$$I_R=2c_1I_P-I_{N'}Kc_0\sin\phi+jI_{N'}Kc_0\cos\phi \quad (21a)$$

and equation 33 becomes

$$T=4\frac{I_P^2}{32.5F}c_1(1-c_1/3)-\frac{2KI_PI_{N'}}{32.5F}\times[c_1(1-c_0/3)+c_0(1-c_1/3)]\sin\phi+\frac{I_{N'}^2}{32.5F}Kc_0(K-Kc_0/3) \quad (35)$$

in which a negative torque term now appears.

Bibliography

1. Relay Systems Utilizing Communication Facilities, J. H. Neher. Electrical Engineering, March 1933, pages 162–8.

2. A Single-Element Differential Pilot-Wire Relay System, E. L. Harder and M. A. Bostwick. *The Electric Journal*, November 1938, pages 443–8.

3. Recent Developments in the Protection of Three-Phase Transmission Lines and Feeders, T. W. Ross and H. G. Bell. IEE *Journal*, volume 68, July 1930, pages 801–52.

4. The Metropolitan-Vickers "Translay", T. W. Ross. *Metropolitan-Vickers Gazette*, November 1929, pages 414–19.

5. A Single-Element Polyphase Directional Relay, A. J. McConnell. Electrical Engineering (AIEE Transactions), January 1937, pages 77–80.

6. Pilot-Wire Relay Protection, E. E. George and W. R. Brownlee. Electrical Engineering (AIEE Transactions), November 1935, pages 1262–9.

7. Relaying of High-Voltage Interconnections, H. P. Sleeper. Electrical Engineering, June 1933, pages 402–08.

Vario-Losser Circuits

W. R. BENNETT
ASSOCIATE AIEE

S. DOBA
NONMEMBER AIEE

Synopsis: Methods are given for the design of circuits using "varistor" elements to secure specified variations of loss as a function of input signal. The types of circuits include compressors and expandors using shunt, series, and lattice networks. Formulas for steady-state transmission and distortion in terms of varistor characteristics are developed.

The functions performed in the telephone plant by various automatic gain-control devices such as vogads and compandors have been described in a number of published articles. These devices have the common property that the gain or loss of a portion of the circuit is made to vary in accordance with changes in the transmitted signal. The term vario-losser is used to designate that part of the system in which the change in loss or gain actually occurs. Vario-lossers operating by virtue of the change in gain or plate impedance of vacuum tubes as a function of varying grid bias have been described elsewhere.[1,2,3] In this paper there are discussed the design considerations for certain simple vario-losser circuits which make use of "varistors," that is, nonlinear elements such as copper oxide and silicon carbide in which the resistance is a function of current or voltage, to furnish the desired variation in loss. These circuits have the advantage of low initial cost, stable properties, long life, and simple maintenance requirements.

It should be kept in mind that in general it is not the instantaneous value of the signal wave which controls the loss or gain of the vario-losser, but some more slowly varying quantity such as the "volume" or "envelope." Since "volume"* controlled circuits require control arrangements of a very high degree of complexity, which do not necessarily affect the vario-losser design, we shall limit our discussion to considerations of "envelope" control. The same considerations would of course enter into "volume" control design.[4]

In "envelope" control, a control current or voltage is commonly derived by rectifying the signal and sending the rectified output through a network (for example, a shunt capacitor and series resistance) which discriminates against the higher frequencies. For our purposes, we shall refer to a current or voltage obtained in this way as representing the envelope of the signal and designate its amplitude by capital letters I or V. The instantaneous values will be designated by lower case letters i and v. Furthermore we shall assume that the envelope varies at such a slow rate that what is under consideration is essentially the steady state.

The operating point of and hence the loss produced by the varistors is determined by the amount of current or voltage bias furnished by the control current, which is in turn fixed by the envelope. The range of variations of the instantaneous signal about the operating point is limited to a region in which the varistors are substantially linear. Under these conditions, the wave form of the signal is preserved, and we may say that the ratio of instantaneous signal output to instantaneous signal input is the same as that of envelope output to envelope input. As general equations therefore, we write

$$v_2/v_1=V_2/V_1=A \quad (1)$$

where the subscripts 1 and 2 refer to input and output voltages, respectively and A is a voltage transfer ratio determined by the envelope. If the value of A is determined by V_1, the input voltage, the device is said to be *forward acting;* if A is determined by V_2, the device is said to be *backward acting*. The usual law of operation desired is that in which the output envelope varies as some power of the input envelope, that is:

$$V_2=kV_1^n \quad (2)$$

where k and n are constants. If n is less than unity, the device is called a *compressor*, since a given range of variation of input envelope produces a smaller range of variation in output envelope. When n is greater than unity, the device is called an *expandor*, since the range of variation of envelope is increased by the device.

Paper **40-136**, recommended by the AIEE committee on communication, and presented at the AIEE Pacific Coast convention, Los Angeles, Calif., August 27–30, 1940. Manuscript submitted November 24, 1939; made available for preprinting July 18, 1940.

W. R. Bennett and S. Doba are with Bell Telephone Laboratories, New York, N. Y.

1. For all numbered references, see list at end of paper.

* The term "volume" is used here to designate that quantity measured by the volume indicator.

The value of n is called the *control ratio*.[5] Obviously if n is equal to unity the device has a fixed loss or gain and does not operate as a vario-losser.

From (1) and (2),

$$A = kV_1^{n-1} \tag{3}$$

and

$$A = k^{1/n}V_2^{1-1/n} \tag{4}$$

Equation 3 may be regarded as the fundamental equation for forward acting vario-lossers, and 4 as the corresponding equation for backward acting vario-lossers. In applications to the design of specific circuits, however, it is more convenient to have the constant k appearing above expressed in terms of the loss or gain at some particular value of load, for example, the maximum operating value. We shall represent the reference condition by a zero subscript, that is, $A = A_0$, $V_1 = V_{10}$, $V_2 = V_{20}$, etc. Equations 3 and 4 then become

$$A = A_0(V_1/V_{10})^{n-1} \tag{3a}$$

$$A = A_0(V_2/V_{20})^{1-1/n} \tag{4a}$$

If the input and output impedances terminating the vario-losser are equal, the loss in decibels is $20 \log_{10} (1/A_0)$ when the input voltage is V_{10} and the output voltage is V_{20}.

Some discussion should be inserted here concerning the actual current-voltage characteristics available in typical varistor elements. In order that a vario-losser may operate satisfactorily over the range of inputs desired, varistor elements must be provided whose resistances can be controlled in the desired manner over a similar range. Anticipating some of the results derived in the next section, dealing with specific circuit arrangements, we point out that a particularly suitable type of curve for varistors from the theoretical standpoint is that in which the current is an exponential function of the voltage over a considerable range. That such behavior can actually be realized to within small error except for low currents is indicated by the measured curve, figure 1, for copper oxide. Semilogarithmic co-ordinate paper is used, which yields a straight-line graph when the function plotted is exponential. Circuits in which the exact form of the varistor characteristic is not critical also exist; they will be discussed under the section on marginal detector types.

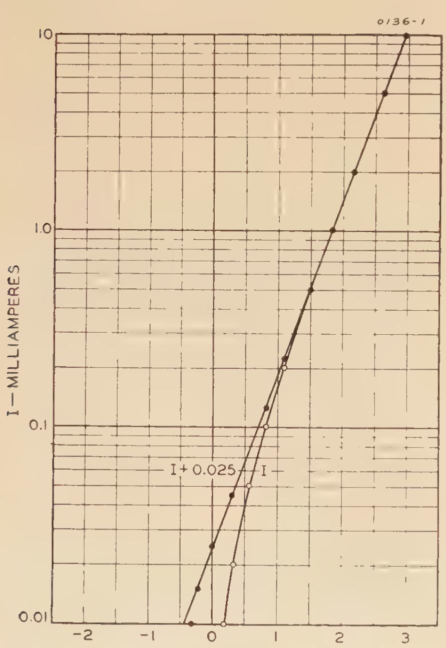
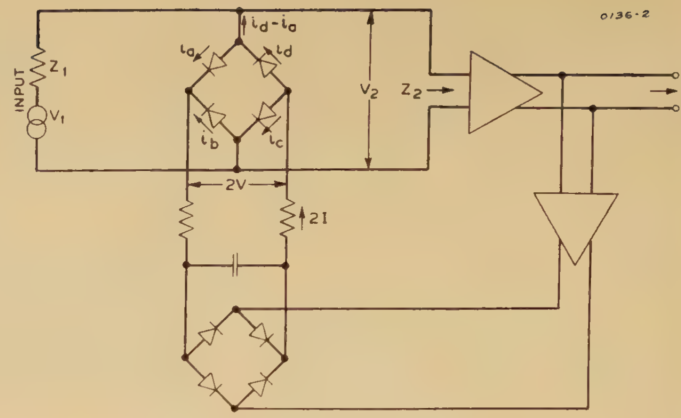


Figure 1. Current versus voltage for typical copper-oxide varistor

Figure 2. Shunt-type backward-acting vario-losser



It should be noted also that in supplying the bias derived from the envelope for controlling the varistor resistances, minimum complexity is secured if the biasing current or voltage is made linearly proportional to the envelope amplitude. It will appear from the discussion to follow, that the combination of a linear current relation with the exponential varistor characteristic is particularly favorable to compression or expansion in the ratio of 2:1. No such simple results are obtained with voltage-controlled devices. We shall therefore confine our treatment to current-controlled devices with the exception of one type of voltage-controlled vario-losser which has the interesting property that a continuous variation of the compression or expansion ratio may be secured.

The general problem is then that of determining the varistor characteristic to obtain the required exponent n with a suitable—generally a linear—rectifier.

Types of Vario-Losser Circuits

From the standpoint of circuit configuration, vario-lossers may be classified as either of the two-terminal or four-terminal type, depending on whether the varistor combination is inserted merely as an impedance element or as a general transmission network. The two-terminal class may be further subdivided into the series and shunt types. The four-terminal class will be represented in this discussion by the lattice type, which is sufficiently general for illustrative purposes.

Two-Terminal Networks

Shunt Type

A shunt-type vario-losser may be constructed by shunting the signal path with nonlinear elements having low resistance compared to that of the remainder of the circuit. A typical circuit of the backward-acting type is shown in figure 2. A portion of the output voltage is amplified and rectified, the rectified current is transmitted through a capacitance-resistance network and then introduced into a varistor bridge. The pair of terminals of the bridge which are conjugate to the bias input are connected directly across the signal input circuit. If r represents the a-c resistance of the varistor bridge shunted across the signal circuit and Z_1, Z_2 the input and output signal circuit impedances, respectively

$$A = \frac{V_2}{V_1} = \frac{rZ_2}{Z_1Z_2 + r(Z_1 + Z_2)} \tag{5}$$

If r is small compared with $Z_1Z_2/(Z_1 + Z_2)$, the impedance of Z_1 and Z_2 in parallel, we have approximately

$$A = r/Z_1 \tag{6}$$

The resistance r varies with the bias current which is in turn proportional to V_2. Let I represent the bias current through and V the bias voltage across one varistor element. For simplicity the elements are assumed to be identical; it follows that r is also the a-c resistance of one element. Then

$$r = dV/dI \tag{7}$$

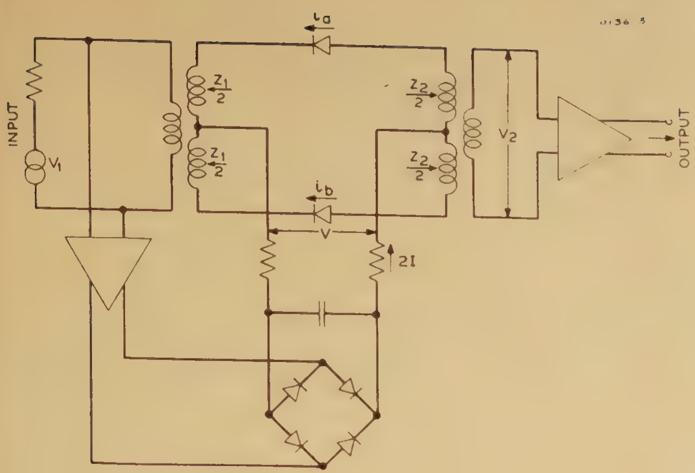


Figure 3. Series-type forward-acting vario-losser

If the impedance of the varistor bridge is low compared with the internal impedance of the rectifier-filter circuit, I is proportional to V_2 and may be written as

$$I = I_0 V_2/V_{20} \tag{8}$$

Substituting the appropriate expression for A from (4a) in (6) and (7)

$$r = Z_1 A_0 (V_2/V_{20})^{1-1/n} = dV/dI \tag{9}$$

whence, substituting (8),

$$dV = r_0 (I/I_0)^{1-1/n} dI \tag{10}$$

Integrating, we thus obtain the general current-voltage relation for the typical varistor element, necessary to make the device satisfy (2),

$$V = \frac{r_0 I_0}{2-1/n} (I/I_0)^{2-1/n} + C$$
$$= V_0 (I/I_0)^{2-1/n} + C \tag{11}$$

The value of the integration constant C must be zero if zero bias is to be included in the operating range, since current and voltage vanish simultaneously. The particular case $n = {}^1/_2$, gives the simple solution of (10),

$$I = I_0 e^{(V-V_0)/r_0 I_0} \tag{12}$$

An exponential current-voltage relation is thus appropriate for a shunt-type backward-acting 2:1 compressor. Since (12) gives a nonzero value of current when the voltage is zero, it cannot be satisfied exactly by physical materials, but it can be made to hold with sufficient accuracy for all except small values of V.

Similarly, for a shunt-type forward-acting device, we substitute, $I = I_0 V_1/V_{10}$ and make use of (3a). We then find

$$V = \frac{r_0 I_0}{n} (I/I_0)^n + C = V_0 (I/I_0)^n + C \tag{13}$$

as the ideal current-voltage curve, and as before the value of C is zero for physical elements. This equation indicates that a material in which the current varies as the mth power of the voltage is suitable for a forward acting shunt type m:1 compressor.

If two shunt type backward acting vario-lossers with exponential varistors such as described above are connected in tandem with a separating pad or amplifier between and equal bias currents proportional to V_2, the output envelope of the second, are supplied to each losser, we would have for the over-all combination,

$$A = b(r/Z_1)^2 \tag{14}$$

From (12), $r = \alpha/I$, α = constant, and since $I = aV_2$,

$$A = \frac{b r_0^2}{Z_1^2} (V_{20}/V_2)^2 \tag{15}$$

Comparing with (4a), then

$$n = 1/3, \; A_0 = b r_0^2 / Z_1^2 \tag{16}$$

This gives a practical method of constructing a 3:1 compressor using exponential varistors. It is also readily demonstrated that the output of the first losser is compressed in the ratio 3:2. In a similar manner, using more units, we may obtain other ratios.

Series Type

Figure 3 shows a forward-acting vario-losser of the series type. Let the total a-c resistance inserted in the circuit by the nonlinear branches be r. We readily calculate

$$A = V_2/V_1 = \frac{Z_2}{Z_1 + Z_2 + r} \tag{17}$$

If r is large compared with $Z_1 + Z_2$.

$$A = Z_2/r \tag{18}$$

From (3a),

$$r = \frac{Z_2}{A_0} (V_1/V_{10})^{1-n} = 2dV/dI \tag{19}$$

If

$$I = I_0 V_1/V_{10} \tag{20}$$

$$2dV = r_0 (I/I_0)^{1-n} dI \tag{21}$$

Integrating

$$V = \frac{r_0}{2(2-n)} (I/I_0)^{2-n} +$$
$$C = V_0 (I/I_0)^{2-n} + C \tag{22}$$

The particular case $n = 2$ gives the simple solution of (21),

$$I = I_0 e^{2(V-V_0)/r_0 I_0} \tag{23}$$

An exponential current-voltage relation is thus found to be also appropriate for a series type forward acting 2:1 expandor.

For a backward acting series type vario-losser, we substitute $I = I_0 V_2/V_{20}$, make use of (4a), and find

$$V = \frac{r_0 I_0}{2} (I/I_0)^{1/n} + C = V_0 \left(\frac{I}{I_0}\right)^{1/n} + C \tag{24}$$

This indicates a method of realizing an n:1 expandor from varistor elements in which the current varies as the nth power of the voltage.

Four-Terminal Networks

Lattice Type

The two-terminal networks just described have the defect that the impedance of the vario-losser network must be either small or large compared with the impedance of the signal circuit; hence the

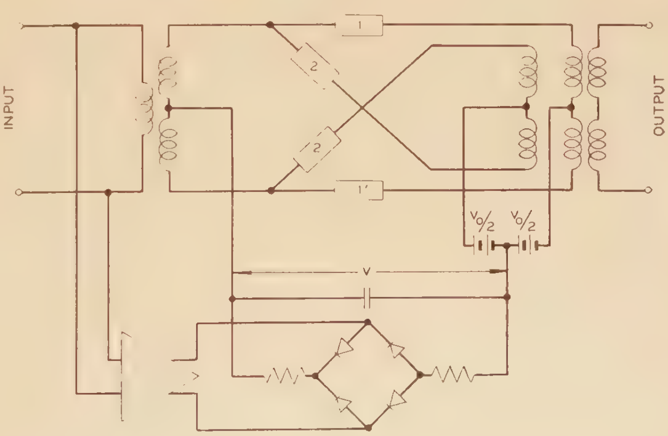


Figure 4. Lattice-type forward-acting vario-losser

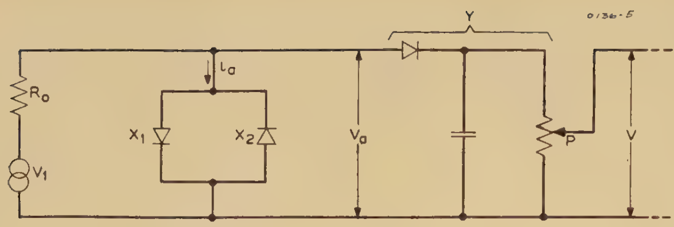


Figure 5. Control circuit for voltage-operated vario-losser giving variable expansion or compression ratio

minimum loss introduced may be excessive, and troublesome reflections caused by the mismatch may result. These difficulties may be avoided by using a lattice arrangement of varistors. In figure 4, the series varistor elements 1, 1′ have biasing voltage $(V_0+V)/2$ and a-c resistance r_1, and the shunt varistor elements 2, 2′ have biasing voltage $(V_0-V)/2$, and a-c resistance r_2. Here V_0 is a fixed direct voltage derived from a battery and V is a varying control component derived from the envelope of the signal wave. The input and output impedances of the signal circuit are assumed real and equal to R. From the equations of a lattice-type network:

$$I_1=\frac{V_1}{2}\left(\frac{1}{R+r_1}+\frac{1}{R+r_2}\right) \tag{25}$$

$$I_2=\frac{V_1}{2}\left(\frac{1}{R+r_1}-\frac{1}{R+r_2}\right) \tag{26}$$

where I_1 and I_2 are input and output currents respectively. If we let

$$r_1=Rf(V) \tag{27}$$

it follows that

$$r_2=Rf(-V) \tag{28}$$

Equations 25 and 26 then become

$$I_1=\frac{V_1}{2R}\left[\frac{1}{1+f(V)}+\frac{1}{1+f(-V)}\right] \tag{29}$$

$$I_2=\frac{V_1}{2R}\left[\frac{1}{1+f(V)}-\frac{1}{1+f(-V)}\right] \tag{30}$$

These equations permit of a useful simplification if

$$f(-V)=1/f(V) \tag{31}$$

a functional equation which is satisfied by the exponential,

$$f(V)=e^{-\alpha V} \tag{32}$$

The negative sign is selected for the exponent because in the varistors used, the resistance decreases as the voltage increases. Substituting (31) in (29) and (30),

$$I_1=V_1/2R \tag{33}$$

$$I_2=\frac{V_1}{2R}\,\frac{1-f(V)}{1+f(V)} \tag{34}$$

Equation 33 shows that the input impedance to the lattice is a constant resistance matching that of the signal circuit. When the relation (32) is substituted in (34), and the output voltage is introduced to compare with (2),

$$V_2=I_2R=\frac{V_1}{2}\tanh\frac{\alpha V}{2} \tag{35}$$

From (2), then

$$A=\frac{1}{2}\tanh\frac{\alpha V}{2} \tag{36}$$

If $\alpha V/2$ is small we have approximately,

$$A=\frac{\alpha V}{4}=A_0V/V_0 \tag{37}$$

If the device is forward-acting, we equate (3*a*) and (37), and get

$$V=V_0(V_1/V_{10})^{n-1} \tag{38}$$

We note that V is directly proportional to V_1 if $n=2$; hence a forward-acting lattice type gives a simple method of constructing a 2:1 expandor. If the device is backward acting, we equate (4*a*) and (37), giving

$$V=V_0(V_2/V_{20})^{1-1/n} \tag{39}$$

and V cannot be made directly proportional to V_2 except when n approaches infinity. The lattice type circuit is therefore best suited for a forward acting 2:1 expandor. A 2:1 compressor may however be realized by putting a 2:1 expandor in the negative feedback path of an amplifier. If an n:1 expandor is inserted in the feedback path in such a direction as to make the feedback negative, we have

$$V_g=V_1-\beta V_2^n \tag{40}$$

where V_g is the actual input voltage of the amplifier, and

$$V_2=\mu V_g=\mu V_1=\mu\beta V_2^n \tag{41}$$

or

$$V_2+\mu\beta V_2^n=\mu V_1 \tag{42}$$

If $\mu\beta V_2^n$ is made large compared with V_2, we have approximately,

$$V_2=(V_1/\beta)^{1/n} \tag{43}$$

and an n:1 compressor is secured. Similarly an n:1 expandor can be realized by inserting an n:1 compressor in the feedback path.

To find the characteristic required for the varistors in the lattice type, we write from (27), (32), (37),

$$r_1=dV/dI=Re^{-4A_0V/V_0} \tag{44}$$

from which by integration

$$I=\frac{V_0}{4A_0R}e^{4A_0V/V_0}+C=\frac{1}{4A_0R}(e^{4A_0V/V_0}-1) \tag{45}$$

if $I=0$ when $V=0$. An exponential relation between voltage and current is thus found to be suitable for a lattice-type losser element as well as the shunt and series types. That a function of form (45) can actually be realized over a wide range including bias values near zero is indicated by the curve of $I+0.025$ in figure 1.

It is to be noted from (36) that as V becomes large, the hyperbolic tangent approaches unity, and hence the voltage transfer ratio approaches a constant. The lattice may therefore be used as a *limited range expandor*, that is, to expand small inputs in the ratio of 2:1, while leaving large inputs unaffected. Likewise when placed in the feedback path of an amplifier, the lattice may be used to obtain a 2:1 *limited range compressor*, and a combination of these forms a *limited range compandor*.

Variable-Ratio Device

In figure 5 is shown a device differing from those previously discussed in that the control is on a voltage basis rather than current. The resistance of the varistor combination X_1, X_2 is made small at all times compared with the resistance R_0 and that of the rectifier-filter circuit Y. We therefore have approximately

$$i_a=\frac{V_1}{R_0} \tag{46}$$

Furthermore if the varistors have exponential current-voltage relationships, the voltage v_a across the varistor combination and the current i_a must satisfy the equation

$$|i_a|=\alpha e^{\beta|v_a} \tag{47}$$

with the additional proviso that i_a is an odd function of v_a because of the oppositely poled pair of elements.* It follows that

$$|v_a|=\frac{1}{\beta}\log\frac{|i|}{\alpha}=\frac{1}{\beta}\log\frac{|v_1|}{\alpha R_0} \tag{48}$$

Now considering the rectifier-filter circuit Y, let the output voltage V be proportional to V_a, the envelope of v_a, and V_a be related to the envelope V_1 of the

voltage v_1 in the same manner as v_a and v_1 are related by (48). Then

$$V = gV_a \tag{49}$$

where g varies between 0 and 1, as determined by the setting of the potentiometer P, and

$$V_a = \frac{1}{\beta} \log \frac{V_1}{\alpha R_0} \tag{50}$$

If the voltage V is used as bias on the varistor elements of a vario-losser circuit, with the varistor impedance high enough not to affect the relation between V and V_1 appreciably, we should have, assuming varistor elements which have the same exponential characteristic as (47),

$$1/r = dI/dV = d(\alpha e^{\beta V})dV$$
$$= \alpha\beta e^{\beta V}$$

Hence

$$r = \frac{1}{\alpha\beta} e^{-\beta V} = \frac{1}{\alpha\beta} e^{-\beta g V_a}$$
$$= \frac{1}{\alpha\beta} e^{-g \log \frac{V_1}{\alpha R_0}} = \frac{1}{\alpha\beta}\left(\frac{V_1}{\alpha R_0}\right)^{-g} \tag{51}$$

If the vario-losser is of the shunt type, we have from (6),

$$A = kV_1^{-g}, \quad k = 1/\alpha\beta Z_1(\alpha R_0)^{-g} \tag{52}$$

Comparing with (3) and (4), we then have the results that for a backward-acting shunt type, $n = 1-g$; while for a forward-acting shunt type, $n = 1/(1+g)$. Similarly, if the vario-losser is of the series type, we make use of (18) and find

$$A = kV_1^{g}, \quad k = \alpha\beta Z_2(\alpha R_0)^{g} \tag{53}$$

whence for forward action, $n = 1+g$, and for backward action, $n = 1/(1-g)$. Since g may be varied continuously between the limits zero and unity, any positive value of n may theoretically be obtained by choosing from the above four types. The ranges of n available from each type are:

	n	Use
Shunt type, forward acting	0 to 1	Compressor
Shunt type, backward acting	1/2 to 1	Compressor
Series type, forward acting	1 to 2	Expandor
Series type, backward acting	1 to ∞	Expandor

Marginal-Detector Types

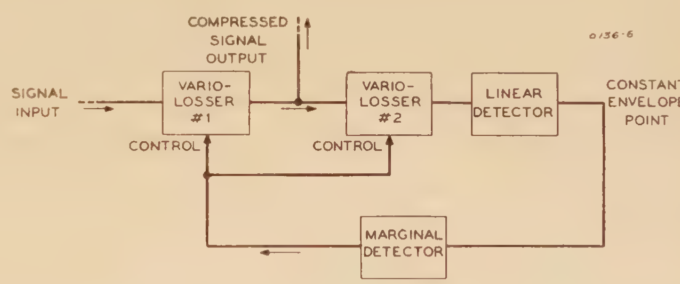
The losser circuits so far described require that the varistor elements have specific current-voltage characteristics, for example, the exponential form, in order to yield the desired mode of operation. It is possible to construct vario-losser circuits to obtain specified ratios of compression or expansion without requiring any property of the varistors other than that of resistance variable with bias. This is accomplished by introducing an auxiliary device, the so-called "marginal detector." A marginal detector may be defined for our purposes as a device which delivers no output when the input is below a certain fixed value, and increases its output very rapidly as the input is increased very slightly through the critical value. A vacuum-tube detector with grid biased negatively beyond the cut-off is an approximation to the ideal marginal detector. If the input of a marginal detector is taken from the output envelope of the signal (see figure 6) and the marginal detector output is used as bias on varistors in a shunt-type vario-losser, no effect occurs when the output is below the marginal value. When the marginal value is exceeded the loss in the shunt varistors increases rapidly with the result that the output cannot appreciably exceed the marginal value. Such an arrangement therefore acts as an envelope limiter.

Now consider the result of using two identical shunt losser circuits in succession as in figure 6 with the same biasing current supplied to each from the marginal detector. The envelope is evidently held constant at the output of the second losser whenever the input to the first exceeds a critical value. Since the two lossers are identical, each must have the same loss. Let x_0 represent the total loss in decibels in the two lossers when the critical input value is not reached. Then if the input to the first losser is x decibels above the critical value, the loss in each of the two lossers is $(x+x_0)/2$ decibels. The output of the first losser therefore increases by $x/2$ decibels when the input increases by x decibels and is therefore compressed in a ratio of 2:1. If three losser units are used instead of two, the output of the first is compressed 3:2 and the output of the second 3:1. In general if n units are used, the output of the mth unit is compressed by the ratio $n/(n-m)$.

A 2:1 expandor may be realized by means of two lossers and a marginal detector, as shown in figure 7. The bias must in this case be supplied by the two lossers in such a way that the loss decreases in the first and increases in the second with the increasing bias. If the amount of decrease in the first is made equal to the amount of increase in the second, the output of the first losser is expanded in the ratio of 2:1.

The marginal detector circuits have the obvious advantage of not being limited by the types of varistor characteristics available, but this is offset by the added complication of the marginal detector itself, which may offer a troublesome adjustment and maintenance problem.

Figure 6. 2:1 compressor of marginal-detector type



Distortion

It is of course necessary for satisfactory operation that the distortion of the signal resulting from transmission through the vario-losser path be held to a low value. Quantitative estimates of the distortion can be obtained by considering the case of a single-frequency input. The envelope then becomes a constant, and the bias applied to the typical varistor element consists of a direct current. The instantaneous voltage across a particular varistor element is the sum of the bias voltage and the voltage produced by the signal. Substitution of this instantaneous voltage in the current-voltage relation for the varistor element enables the approximate calculation of the distorted component of signal current.

We may illustrate by considering the shunt-type vario-losser circuit, figure 2. If the signal input is represented by

$$v_1 = V_1 \cos pt \tag{54}$$

the signal output is to a first approximation, also sinusoidal and of the form,

$$v_2 = V_2 \cos pt \tag{55}$$

If all four varistor elements are identical,

* This arrangement is necessary in the case of copper oxide. In the case of silicon carbide, the material itself would have the proper symmetry and one element would suffice.

each with the instantaneous current-voltage relation, $i=f(v)$,

$$i_a=i_c=f\left(V+\frac{1}{2}V_2\cos pt\right) \tag{56}$$

$$i_b=i_d=f\left(V-\frac{1}{2}V_2\cos pt\right) \tag{57}$$

$$i_d-i_a=f\left(V-\frac{1}{2}V_2\cos pt\right)-f\left(V+\frac{1}{2}V_2\cos pt\right)$$
$$=-f'(V)V_2\cos pt-\frac{f'''(V)}{3!}\frac{V_2^3}{4}\cos^3 pt-\ldots \tag{58}$$

The principal distortion component is thus a third harmonic

$$i_d-i_a=-\frac{f'''(V)}{24}V_2^3\cos^3 pt \tag{59}$$

This current may be considered to be generated in the varistor bridge and to divide between the impedances Z_1 and Z_2. No even harmonics appear in the output circuit because of the assumed balance of the bridge. The third harmonic voltage appearing across the output is

$$v_{23}=-\frac{Z_1Z_2f'''(V)V_2^3}{96(Z_1+Z_2)}\cos 3\,pt \tag{60}$$

The significance of the negative sign is that the phase of the third harmonic is such as to flatten the peak of a sine wave, which is to be expected since the shunting action of the varistors is greater for large amplitudes. It is convenient to assume $Z_1=Z_2$, and take the ratio of the maximum value of v_{23} to the maximum fundamental output voltage amplitude V_2, giving

$$\frac{V_{23}}{V_2}=\frac{Z_1f'''(V)V_2^2}{192} \tag{61}$$

For a series-type losser, we have, referring to figure 3,

$$i_a=f\left(V-\frac{V_1}{2}\cos pt\right) \tag{62}$$

$$i_b=f\left(V+\frac{V_1}{2}\cos pt\right) \tag{63}$$

$$i_b-i_a=f'(V)V_1\cos pt+\frac{V_1^3f'''(V)}{4.3!}\cos^3 pt+\ldots \tag{64}$$

$$V_{23}=\frac{V_1^3Z_2f'''(V)}{96}=\frac{f'''(V)}{96Z_2^2}r^3V_2^3 \tag{65}$$

$$\frac{V_{23}}{V_2}=\frac{f'''(V)}{12[f'(V)]^3}(V_2/Z_2)^2 \tag{66}$$

The above principles may be illustrated by working out an example. Suppose it is desired to use copper-oxide varistors having the characteristic shown in figure 1 in a shunt-type vario-losser such as shown in figure 2 with third harmonic at least 30 decibels down on fundamental over a 30-decibel range of loss variation. Also given that the maximum amount of direct current per varistor is four milliamperes. It is required to find the maximum output voltage permissible and the impedance which should face the varistors. We assume $Z_1=Z_2$. The characteristic of figure 1 may be represented by the equation

$$I=0.025(e^{2V}-1) \tag{67}$$

where V is in volts and I in milliamperes. By differentiation, we find that the resistance in ohms is given by

$$r=2.10^4e^{-2V} \tag{68}$$

and that the third derivative is

$$f'''(V)=\frac{4}{r} \tag{69}$$

Substituting in equation 61, we find for the ratio of third harmonic to fundamental,

$$\frac{V_{23}}{V_2}=\frac{0.0208Z_1V_2^2}{r} \tag{70}$$

The greatest distortion occurs at the maximum load. Calling the maximum output voltage V_{20}, and noting that distortion 30 decibels down is equivalent to a voltage ratio of 0.0316, we write as one requirement:

$$\frac{Z_1V_{20}^2}{r_0}=1.53 \tag{71}$$

The required 30-decibel variation in loss is to be obtained as r is increased from the minimum permissible value specified by (71) to its maximum value, which occurs with zero bias. If we assume that the maximum value of r is large compared with Z_1, we see from (5) and (6) that the value of A varies from $^1/_2$ to r_0/Z_1. The total variation in loss is therefore 20 $\log_{10} 2r_0/Z_1$, and if this is to be 30 decibels we must have

$$r_0/Z_1=0.0158 \tag{72}$$

Substituting (72) in (71), we find $V_{20}=0.155$ volt. Since the bias current I_0 available for each varistor at this value of V_{20} is four milliamperes, the corresponding voltage V_0 across each varistor is, from figure 1, 2.5 volts, and from (68), the resistance r_0 is 132.5 ohms. From (72), the terminating impedance Z_1 should be 8,390 ohms.

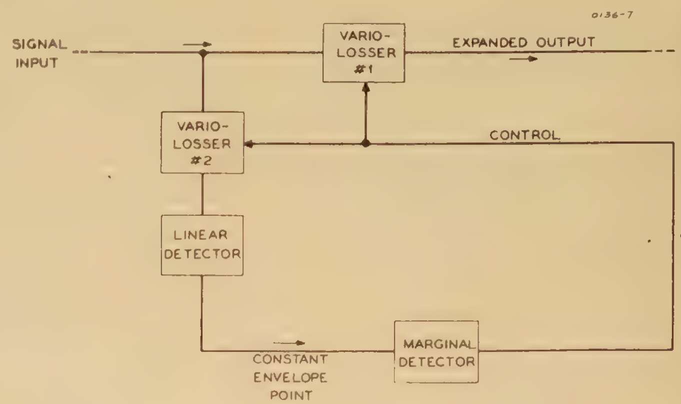


Figure 7. 2:1 expandor of marginal-detector type

References

1. The Compandor—An Aid Against Static in Radio Telephony, R. C. Mathes and S. B. Wright. *B.S.T.J.*, volume 13, 1934, number 3, 315–32.

2. A Vogad for Radiotelephone Circuits, S. B. Wright, S. Doba, and A. C. Dickieson. IRE *Proc.*, volume 27, 1939, number 4, 254–7.

3. Devices for Controlling Amplitude Characteristics of Telephonic Signals, A. C. Norwine. *B.S.T.J.*, volume 17, 1938, number 4, 539–54.

4. For a general discussion of other design considerations see Amplitude Range Control, S. B. Wright. *B.S.T.J.*, volume 17, 1938, number 4, 520–38.

Possibilities and Methods of Extending a Carrier Current Relay Channel to Other Uses

R. M. SMITH
ASSOCIATE AIEE

S. L. GOLDSBOROUGH
ASSOCIATE AIEE

CARRIER-CURRENT relaying is now well established as the most complete type of protection. It has had sufficient field experience to well justify the fundamental principles on which it is founded and the manner in which it has been worked out. As it often happens, the solution of one problem will lend itself to another similar problem. This seems to be the case of carrier-current relaying as it has provided the communication channel which might be available to solve other problems involving the transmission and reception of signaled information. This common solution to two problems naturally lessens the economic factors which relieves each problem of the strain of carrying the entire burden. Other problems involving the use of communication means which could be provided by the relay channel are: telemetering, supervisory control, load control, communication, remote tripping, etc. The addition of these other functions to the carrier channel, while not involving serious technical difficulties, nevertheless, requires the consideration of some problems. Methods are available and actual installations have been made involving various combinations of additional uses of the relay channel.

While the accommodation of several quantities on the carrier channel may seem to violate the old adage that two bodies cannot occupy the same space at the same time, nevertheless, the telephone industry has shown for a number of years that several separate sets of information-carrying quantities can occupy the same transmitting medium. There are two aspects of the problem of extending the functions of a carrier-current relay channel involving different degrees of complication. One method is to add functions but not require that they be carried on at exactly the same time. This way lessens the amount of apparatus required but introduces the necessity for compromises in the desired characteristics. There are a large number of combinations of functions which can be added to the relay function without materially adding to the equipment provided they are co-ordinated and compromised in the right manner. The manner in which the problem is solved is specific for each application. It is not the purpose of this paper to consider all of these combinations but merely to point out some of the possibilities.

The other method assumes that all the functions performed by the carrier channel must be carried on concurrently. This means that additional equipment must be provided to render the functions entirely independent of one another and, of course, removes the necessity of imposing any restrictions or compromises.

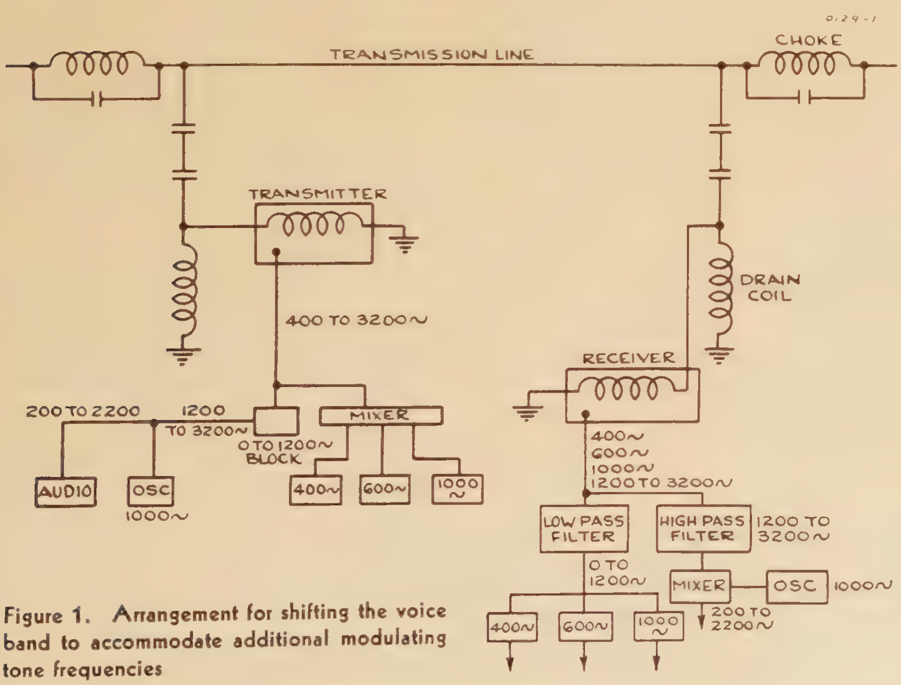


Figure 1. Arrangement for shifting the voice band to accommodate additional modulating tone frequencies

Fundamental Problems

There are a number of fundamental requirements which must be considered in any scheme to extend the use of a relay channel. Since the primary object of the carrier channel in a relay system is to transmit information between the relays at the ends of the protected section, the relays must be capable at all times of starting and stopping the carrier signal regardless of whatever other use is being made of the carrier wave. Any other use of the carrier channel must be temporarily suspended during the occurrence of faults on the system. Ordinarily, this should not seriously interfere with the additional functions since with high-speed relays the time of interruption is small. The loss of a few telemetering impulses or a syllable of speech would hardly be considered serious. Even the interruption occasioned by slow-speed relays clearing a fault elsewhere on the system is not serious. This preferential use of the carrier channel by the relays can always be attained in systems where all of the carrier functions are entirely independent but in systems where compromises are made for the sake of simplicity there may be times when the relays are unable to take control of the carrier. An example is the case where no fault current flows at one end of the line. Here a telemetering impulse or telephone conversation could prevent tripping because there is no relay action at the zero current end to stop the carrier.

There are two ways in which the relay carrier channel can be extended to other uses.

1. The carrier wave itself may be used to carry the intelligence. This method requires the least amount of additional equipment but has limitations in the number of

---

Paper 40-129, recommended by the AIEE committee on protective devices, and presented at the AIEE Pacific Coast convention, Los Angeles, Calif., August 27–30, 1940. Manuscript submitted June 12, 1940; made available for preprinting July 11, 1940.

R. M. SMITH is section engineer and S. L. GOLDSBOROUGH is design engineer, Westinghouse Electric and Manufacturing Company, Newark, N. J.

1. For all numbered references, see list at end of paper.

functions that can be handled. Telemetering can be added by merely "keying" the carrier to send out a set of impulses in which either the rate or the duration of the pulses are used to actuate the telemetering receiver. Communication alone can be easily added, since it requires merely that the carrier be held on continuously. However, communication and telemetering could not be accomplished simultaneously since the one function requires continuous and the other requires impulsed carrier. Furthermore, more than one telemetering quantity cannot be used, since the impulses would interfere.

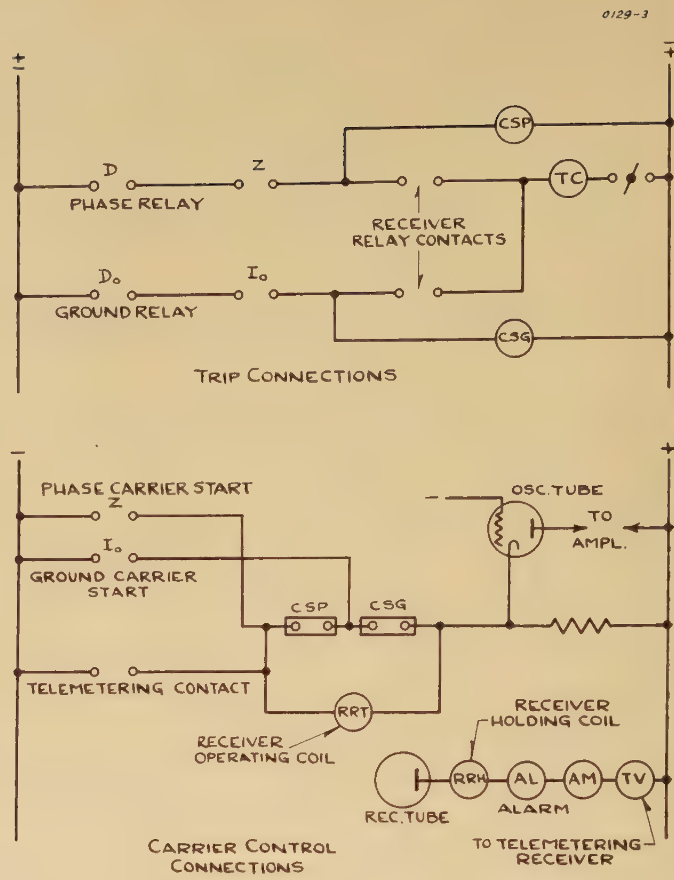
In general, it may be said that if the carrier wave itself is employed, it can take care of only one additional function at a time. If the additional functions do not need to be performed at the same time, then several purposes can be served by the relay carrier channel. Thus, communication, telemetering, supervisory, and remote tripping could be accomplished.

The chief disadvantage of utilizing the carrier wave itself is, as was indicated previously, the possibility of preventing tripping when no fault current occurs at one terminal. In this case, the carrier, if initiated by communication, telemetering, etc., at the end where no fault current flows, cannot be stopped by the relays at this end.

2. A number of tone or modulating frequencies may be imposed upon the carrier and each tone may be used to transmit a separate set of signals. If the tone frequencies are not inside the voice frequency band, communication may also be added. Also, if the relay signal is placed on one of the tones instead of the carrier itself, the difficulty experienced when no fault current flows initially at one terminal is entirely avoided. Assuming that communication is not desired, the number of functions which can be accommodated is limited only by the number of tone frequencies which can be placed in the audio band width which the carrier set will pass. With communication the number of functions is limited by the number of tones that can be placed outside an intelligible voice band but inside the band capable of being passed by the transmitter-receiver set.

The use of a tone frequency means that the carrier wave is modulated by one or more definite audio frequencies, say, 600 and 1,000 cycles. At the receiver end the carrier is demodulated and the tone frequencies are separated by filter circuits. It is obvious that each tone may be used to transmit signals entirely independent of all other tones and this system is, therefore, applicable where the number of additional functions cannot be accommodated by the carrier wave itself.

Figure 3. Schematic diagram of a carrier current relay scheme



Tone Modulating System

Some of the technical aspects of the tone system are as follows:

1. There must be a minimum ratio between the impulsing frequency and the tone frequency. If this ratio is too small, the receiver apparatus will have a tendency to respond to the tone as well as the impulsing frequency

2. There must be a wide enough separation in the tone frequencies to avoid the necessity of sharply tuned filter circuits. If communication is used, the tones must be placed outside the voice-frequency band. An intelligible voice band is from, say, 200 to 2,200 cycles and the band which can be ordinarily passed by the carrier set is approximately 200 to 3,200 cycles. It is thus seen that not more than one or two tone frequencies could be placed either below or above the voice band. If more tones are required, they could be provided either by "cutting holes" in the voice band or by shifting the voice band toward the upper limit of the carrier set. The process of "cutting holes" in the voice band would consist of filtering out say from 900 to 1,100

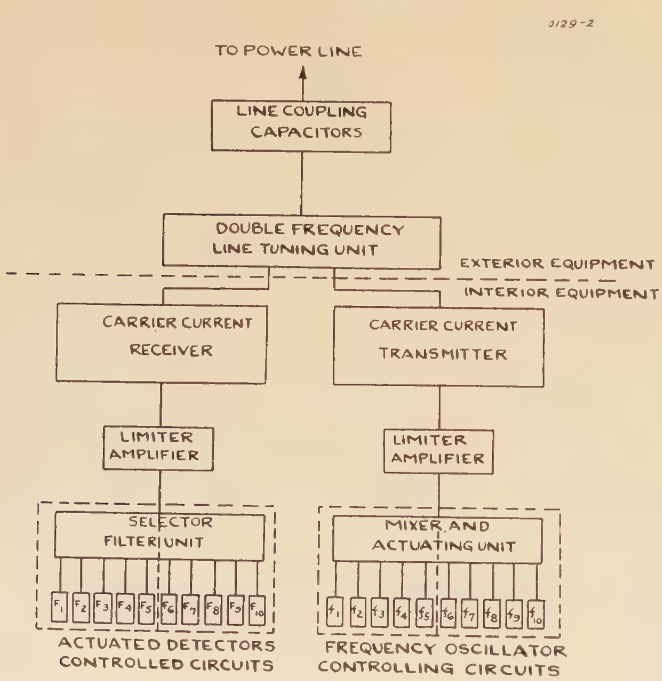


Figure 2. Extensive use of modulating tone frequencies on a carrier current channel

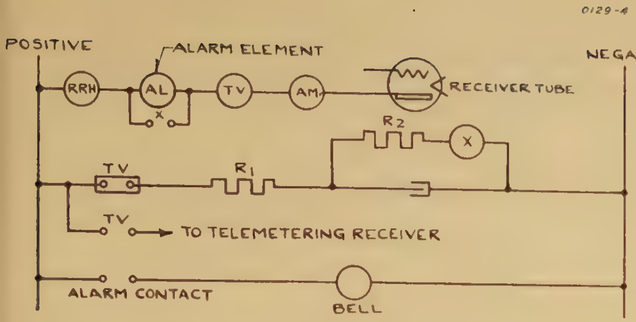


Figure 4. Arrangement to prevent alarm bell response on telemetering impulses

cycles from the voice input to the modulator and then supplying a 1,000-cycle note from an audio oscillator. The absence of the 900 to 1,100-cycle notes would have some tendency to impair the speech quality and, of course, if too many of these holes were cut, the speech would become too poor for intelligible use.

Another method for accommodating speech and tone frequencies would be to shift the voice frequency toward the high end of the receiver band. Assuming 200 to 2,200 cycles sufficient for clear speech, this could be shifted to 1,200 to 3,200 cycles by adding 1,000 cycles. This would give a band of say 100 to 1,200 cycles for tone frequencies. Possible tones of 100, 130, 170, 220, 286, 370, 480, 620, 810, 1,050 could be accommodated with a 30 per cent separation below 1,200 cycles. Figure 1 shows schematically the arrangement needed to accomplish this system. The speech input is heterodyned with the output of a 1,000-cycle oscillator and the sum frequency is passed into the carrier set modulator. A high-pass filter cuts off all frequencies below 1,200 cycles. Separate oscillators producing different tones also feed through a mixing device to regulate the amplitude into the carrier set. At the receiving end frequencies up to 1,200 cycles are first filtered out, leaving the voice band 1,200 to 3,200 cycles from which 1,000 cycles is subtracted by heterodyne action with a 1,000-cycle oscillator. The output of the low-pass filter is further filtered into the individual tones.

To our knowledge, no application of this voice-shift system has yet been made in this country, but it has been used in France.[1] The chief object here is to point out the engineering aspects involved in connection with a very extensive additional use of a carrier relay channel. Figure 2 shows an extensive use of tone frequencies on a carrier-current channel on which communication is not desired.

Telemetering

It is the purpose here to discuss some of the specific problems which occur when the telemetering function is added to the relay carrier channel. There are two types of impulse telemetering systems. One takes account of the rate of the impulses and the other operates on the duration and spacing of impulses. The problems discussed here are based on the system utilizing the rate of impulses. The same problems could, no doubt, be solved in a similar manner for the impulse duration principle. Also, it should be understood that each application of telemetering to a relay carrier channel may involve specific problems requiring a solution applying only to that application and it is not the intention here to cover all of the problems which might arise. Furthermore, no attempt is made here to discuss telemetering systems themselves.

Figure 3 shows schematically a relay carrier scheme.[2] The carrier is initiated by the closure of the impedance or overcurrent contacts, Z or I_0, which impresses negative potential on the oscillator cathode. Carrier is stopped when the directional and impedance contacts, D and Z, close to energize the CSP coil which in turn opens the CSP contact, thus returning the cathode to positive. Carrier is started and stopped in a similar manner by the action of the ground relay contacts, D_0 and I_0. The telemetering contact is placed in parallel with the Z carrier start contact and it is obvious that with this connection the relay contacts can start and stop carrier regardless of what position the telemetering contact is in. At the receiving terminal a relay is placed in the plate circuit of the receiver tube and is actuated by each of the carrier pulses. The contacts of this relay are connected to actuate the telemetering receiver.

At both the sending and receiving terminals there is an alarm relay, AL, whose function is to close contacts when a carrier signal is received and ring an alarm bell. The primary purpose of this alarm bell is to enable the operators at each end of the line to signal each other when it is desired to test the transmission and reception of carrier or to communicate by telephone. Obviously, if telemetering signals are being transmitted, it would be

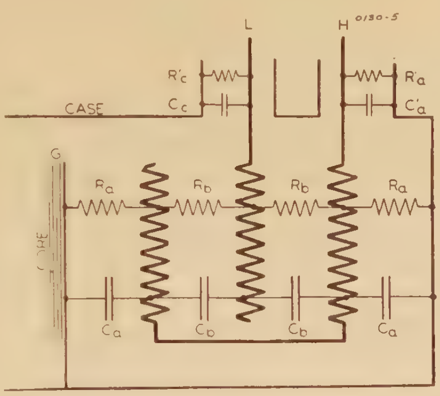


Figure 5. Scheme to stop telemetering from the receiver end

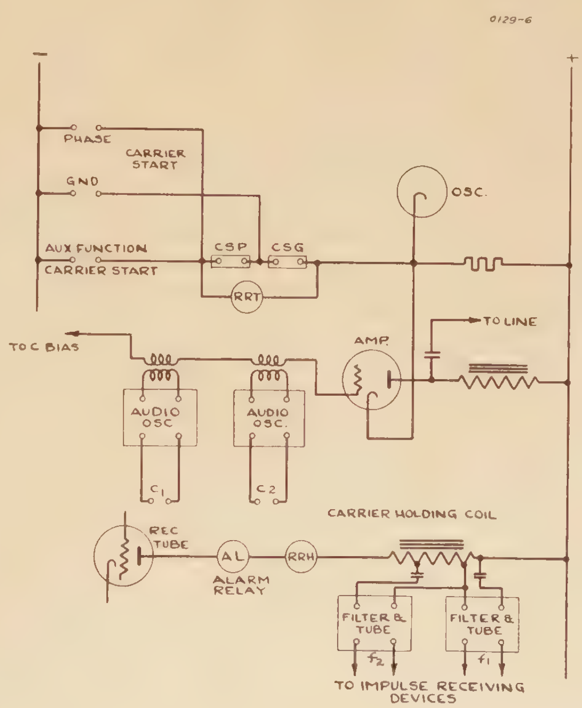
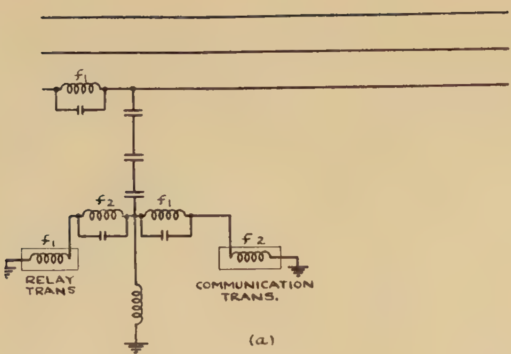
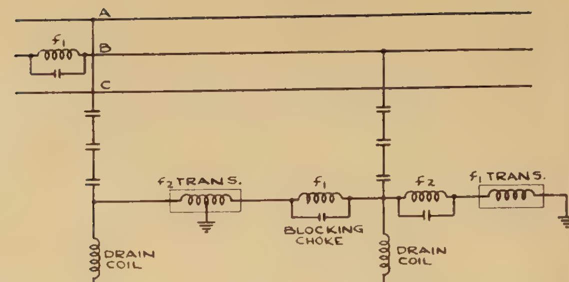


Figure 6. Schematic diagram of modulating tone frequencies



(a)
Relaying & Communication One Phase Wire To Ground

Figure 7

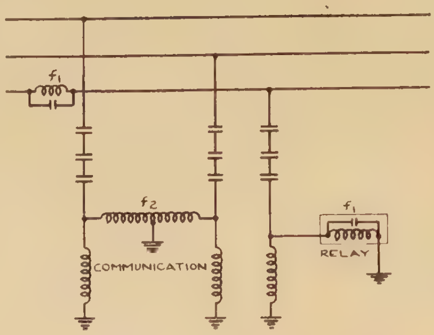


(b)
Communication On A & B Relaying On B To Gnd.

confusing to ring the alarm bell on each signal. Of course, a simple solution is to disconnect the bell, but this prevents the bell from performing its normal signaling function.

An arrangement to prevent the alarm relay from operating on telemetering impulses but permit it to operate when it is desired to signal is shown in figure 4. During the reception of telemetering signals the alarm relay coil, *AL*, is short-circuited by the *X* contact operated by the *X* relay which is energized through the resistors, R_1 and R_2, and the *TV* back contact. The *TV* relay operates on each carrier impulse and opens its back contact, but the *X* coil is energized by the capacitor discharge until the *TV* contact closes again. When it is desired to operate the alarm bell, the carrier is held on at the remote station for approximately one second. This opens the *TV* contact and after the capacitor has discharged, the *X* relays drops out, thus allowing the alarm relay, *AL*, to pick up on the carrier signal.

Another problem which arises is the necessity of stopping the transmission of signals, from the receiver end, so that a function can be performed in the opposite direction. Thus, telemetering from an unattended station to an attended station may be stopped so that a supervisory signal may be sent to control breakers at the unattended station. Figure 5 depicts a scheme to accomplish this feature. During the transmission of telemetering impulses the relay contacts, *TV*, close on each impulse. The duration of the impulse, however, is not long enough to allow the time delay relay, *TD*, to pick up, thus the *SG* relay is de-energized and its back contact closed, allowing the telemetering contact, *T*, to transmit impulses. When it is desired to operate the supervisory from the attended station, the carrier push button is depressed for a long enough time to close the *TD* relay. This picks up the *SG* which seals itself in and opens its back contact to prevent further transmission of telemetering impulses. After the desired supervisory actions



Seperate Communication & Relaying Channels
(c)

have been performed, the final supervisory action is to open momentarily the contact, *S*, which resets the *SG* relay and telemetering is resumed.

To telemeter more than one quantity simultaneously, it is necessary to "key", modulating tone frequencies instead of the carrier wave itself. Figure 6 shows schematically the apparatus required. Simple vacuum-tube audio oscillators are adjusted to definite frequencies and fed into the grid of the amplifier tube. At the receiving end the carrier wave is demodulated and the plate circuit of the receiver tube contains the tone frequencies. These frequencies are separated and fed to the telemetering receiver devices. At the sending end the audio oscillators are impulsed by the contacts, C_1 and C_2, which are operated by the telemeter transmitter. If signals are sent continuously, the carrier wave must, of course, be held on continuously. If the signaling is intermittent, it would be possible to have the telemetering transmitter also operate the carrier start contact.

Another principle which has been used to enable a single carrier channel to perform more functions and avoid complication is to store the telemetering impulses at the sending end and transmit only at definite intervals. The impulses are merely fed into a mechanical counter and then at regular intervals the accumulated impulses in the counter are transmitted.

Supervisory and Remote Tripping

There are numerous combinations of supervisory, telemetering, and remote tripping which can be applied to a relay carrier-current channel. For instance, the telemetering can be made one point on the supervisory control.

Where supervisory control is installed, it is generally important enough to demand a good pilot circuit. Certain troubles with conventional pilot circuits have brought out the fact that a high-voltage line is not only reliable as a power distributor, but is also just as reliable as a pilot wire. For this reason carrrier-current channels over the high-voltage line itself are more and more being used for supervisory control.

In general, supervisory control requires the transmission of signals in both directions. However, these signals do not need to be sent simultaneously, and, therefore, a single-frequency relay carrier channel is all that is required. It is possible to combine the supervisory system with other functions without complication by making the other functions merely points on the supervisory system.

A relay carrier channel provides an excellent means of tripping a distant breaker when the fault current is too small to actuate the protective relays. A practical example is the case where a transformer bank is included as part of the high-voltage line with no high-voltage breaker. The problem here is to protect the transformer against internal faults which may not draw enough current from the distant end to actuate the line relays. With a carrier channel available, sensitive differential protection can be applied to the transformer, and the tripping of the distant breaker can be initiated by the transmission of a carrier signal. Of course, the local low-voltage breaker is tripped directly by the differential relays. One company in New England has installed this remote tripping scheme on a carrier-protected line which includes a transformer bank at one end and has had

successful results. The differential relays trip the local low-voltage breaker and also cause a coded signal to be sent via the carrier to trip the breaker at the other end of the line. The use of a coded set of carrier impulses eliminates possible trippings on stray interference. The transmission and reception of the code signal required about one-third second. Faster action could be obtained by using one or more modulating tone frequencies instead of applying impulses to the carrier wave itself.

Communication

In applying communication to a relaying carrier-current channel, it should be realized that the carrier channel is primarily for relaying purposes and was not designed as a communication channel. A high-quality communication channel requires a number of characteristics which a relay carrier transmitter-receiver does not possess. When the communication requirements as to quality, distance, number of talking points, etc., become important, it is usually more economical and satisfactory to divorce the communication from the relays by providing a separate channel. In some cases, it is possible to obtain the channel separation but still make some of the apparatus serve both relays and communication.

However, for moderate communication requirements, the relay carrier equipment lends itself admirably to communication purposes. One relay carrier transmitter-receiver has a built-in modulator for this purpose. The type of communication ordinarily provided by a relay carrier channel is known as the "point-to-point-push-to-talk" method. That is, an operator at one station first signals the operator at another station by means of the carrier push button and the alarm bell. After contact has been made, the operator wishing to talk presses a button on the handset to cause carrier transmission. After he is through, the operator at the other end of the line must depress his handset button in order to reply.

Communication on a relay carrier channel is necessarily limited to point-to-point because the relay scheme requires that each line section operate on a frequency of its own, isolated from other sections. Communication through a line sectionalizing point means that the carrier must be by-passed around the station. Obviously, a relay carrier channel cannot be handled this way. It has been suggested that several line sections be coupled together for communication on the relay carrier channel by repeating the voice frequencies around the substation. Such an audio by-pass can be arranged, but a complication introduced is the cascading of the receiver distortion. With several sections coupled in this manner the speech would be unintelligible. Not more than two line sections can be coupled together and still retain a fair quality of speech.

If the importance of the communication function requires operation from several locations, selective calling, and other telephone requirements, then it becomes more economical to provide a separate communication channel and a communication carrier set rather than attempt to adapt a relay carrier channel to this purpose.

In providing an additional carrier channel for communication, some savings may be affected on higher-voltage lines by using a common coupling capacitor to connect the two carrier channels to the high-voltage line. Both relay and communication channels can be on one phase-to-ground, or the communication can be phase-to-phase and the relay channel phase-to-ground. Figure 7*a* shows relaying and communication on one phase-to-ground using one coupling capacitor. No line chokes are shown for the communication frequency, since they are not necessary unless the distances and number of line paths over which the carrier can divide are too great. Figure 7*b* shows the communication phase-to-phase and the relay carrier channel phase-to-ground. Here it is necessary to provide one extra coupling capacitor for the communication. Phase-to-phase communication is more efficient and encounters a lower noise level than phase-to-ground coupling and is generally used where the communication covers a large area.

Conclusions

1. Definite economies can be effected by using a relay carrier channel for other uses. These additional uses will sometimes justify the expense of a relay carrier-current installation.

2. Other functions can be added without much complication, if it is not necessary to perform them simultaneously.

3. Simultaneous performance of two or more functions requires that modulating tone frequencies be provided.

4. The addition of telephone communication limits the number of modulating tone frequencies available for other functions. It is possible to shift the voice-frequency band to accommodate more tone frequencies.

5. If more extensive telephone communication than "point-to-point" is desired, it should be placed on a separate carrier channel.

6. Two separate carrier channels can utilize common coupling capacitors.

Bibliography

1. Perfectionnements aux Systemes de Telecommunication par Courants Porteurs sur Lignes à Haute Tension, Parrisier Publication Conference Internationale des Grands Reseaux Electriques à Haute Tension, 1939.

2. A New High-Speed Distance Carrier-Pilot Relay System, **E. L. Harder, B. E. Lenehan, and S. L. Goldsborough.** AIEE Transactions, 1938 (January section) page 5.

Discussion

Discussion will be found in the 1941 annual Transactions volume and in the June 1941 Supplement to Electrical Engineering—Transactions Section.

Power-Factor Testing of Transformer Insulation

J. B. HODTUM
MEMBER AIEE

Synopsis: This paper points out a method for analyzing the results obtained from dissipation-factor tests of transformer insulation. Experimental data, obtained both from transformer tests, extending over the past three years, and from tests of sample insulation, indicate a definite relation between resistance and capacitance, with varying conditions of temperature and moisture. This relation furnishes an additional means for determining the condition of insulation when considered with other accepted methods.

The physical arrangement of the transformer windings, and the type of test equipment used, affect the tests and should be considered when interpreting results.

THE term, "power-factor testing" of insulation during the past several years has come into wide use. However, it is felt that the use of the dissipation factor is better because it can be more readily determined and is more convenient to use. Dissipation factor is the cotangent of the angle between the voltage and current while power factor is the cosine of the angle.

Equivalent Insulation Circuits

The electrical characteristics of insulation can be represented in the simplest form, for any given frequency, by an equivalent circuit consisting of a single lumped resistance and a single lumped capacitance. The lumped resistance and capacitance may be arranged either in series or in parallel (see figures 1 and 2). However, for this analysis the parallel equivalent circuit has certain advantages over the series circuit and will, therefore, be used throughout.

Since capacitance bridges used for insulation testing read capacitance in terms of the series equivalent circuit, it is necessary to convert these readings to the corresponding resistance and capacitance components of the parallel equivalent circuit. Table II shows the operations necessary to obtain the equivalent parallel resistance and capacitance from the readings of several types of commercial instruments. It will be found that for low values of dissipation factor, the parallel capacitance is approximately equal to the series capacitance. As the dissipation factor increases, however, the difference between the parallel capacitance and the series capacitance increases so that a conversion is necessary for the larger values of dissipation factor.

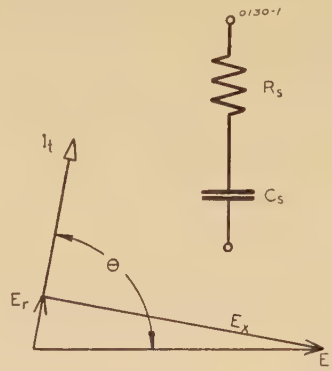


Figure 1. Equivalent series circuit of the insulation

$$\text{Dissipation factor} = \frac{2\pi f C_s R_s}{10^6}$$

When $f=60$ cycles, C in micromicrofarads, R in megohms:

$$\text{Dissipation factor} = \frac{C_s R_s}{2{,}650}$$

Physical Arrangement of Windings

Transformer windings are grouped in various arrangements depending upon the kilovolt-ampere rating, the voltage and the impedance requirements, and whether of shell- or core-type construction.

Figures 3, 4, and 5 show typical winding arrangements or groupings for two winding transformers and the equivalent circuits of such transformers as composed of three major parts as follows:

1. Insulation between high-voltage winding and ground designated by subscript *a*.
2. Insulation between high-voltage winding and low-voltage winding designated by subscript *b*.
3. Insulation between low-voltage winding and ground designated by subscript *c*.

It is recognized that resolving the insulation structure into these very simple forms does not always give a complete picture but this division is used because of its simplicity.

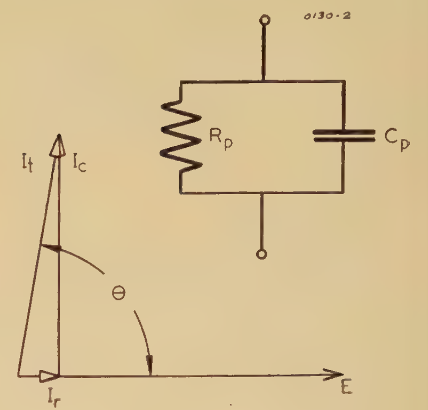


Figure 2. Equivalent parallel circuit of the insulation

$$\text{Dissipation factor} = \frac{10^6}{2\pi f C_p R_p}$$

When $f=60$ cycles, C in micromicrofarads, R in megohms:

$$\text{Dissipation factor} = \frac{2{,}650}{C_p R_p}$$

If the measuring instrument used contains a guard circuit these individual parts of the insulation may be tested directly.

When a guard circuit is not available, it is then necessary to conduct the following three tests:

Test *A*—High-voltage winding to low-voltage winding and ground.

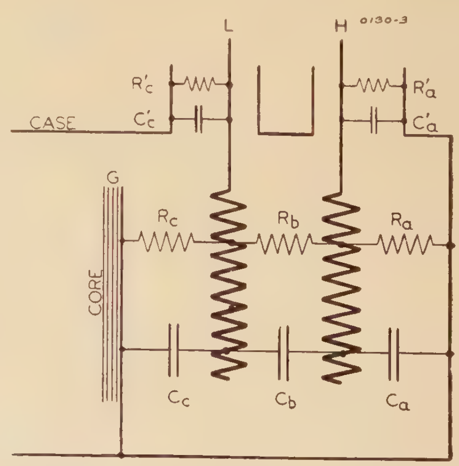


Figure 3. Schematic diagram of a two-winding transformer having core-low-high coil grouping

---

Paper 40-130, recommended by the AIEE committee on electrical machinery, and presented at the AIEE Pacific Coast convention, Los Angeles, Calif., August 27–30, 1940. Manuscript submitted July 1, 1940; made available for preprinting July 12, 1940.

J. B. HODTUM is development engineer, Allis-Chalmers Manufacturing Company, Pittsburgh, Pa.

Table I. Separated Capacitance and Resistance Components for Equivalent Circuits of Figures 3, 4, and 5

From Tests A, B, and G	For Figure 3	For Figure 4	For Figure 5	Part of Insulation
$\frac{1}{2}(C_A+C_G-C_B)=$	C_a+C_a'	C_a'	C_a+C_a'	High voltage to ground
$\frac{1}{2}(C_A+C_B-C_G)=$	C_b	C_b	C_b	High voltage to low voltage
$\frac{1}{2}(C_B+C_G-C_A)=$	C_c+C_c'	C_c+C_c'	C_c'	Low voltage to ground
$\frac{1}{2}\left(\frac{1}{R_A}+\frac{1}{R_G}-\frac{1}{R_B}\right)=$	$\frac{1}{R_a}+\frac{1}{R_a'}$	$\frac{1}{R_a'}$	$\frac{1}{R_a}+\frac{1}{R_a'}$	High voltage to ground
$\frac{1}{2}\left(\frac{1}{R_A}+\frac{1}{R_B}-\frac{1}{R_G}\right)=$	$\frac{1}{R_b}$	$\frac{1}{R_b}$	$\frac{1}{R_b}$	High voltage to low voltage
$\frac{1}{2}\left(\frac{1}{R_B}+\frac{1}{R_G}-\frac{1}{R_A}\right)=$	$\frac{1}{R_c}+\frac{1}{R_c'}$	$\frac{1}{R_c}+\frac{1}{R_c'}$	$\frac{1}{R_c'}$	Low voltage to ground

Test *B*—Low-voltage winding to high-voltage winding and ground.

Test *G*—High-voltage winding and low-voltage winding to ground.

From these tests, the values of R and C of the separate parts of the insulation may be calculated using the relations shown in tables I and II.

Table I shows that the coil grouping materially affects the results and must therefore be considered in the analysis. It will be noted that the capacitance and the resistance components of the high-voltage winding to ground test of figure 4 is a measure of the high-voltage bushings, leads, and terminal boards to ground rather than high-voltage winding to ground. Such cases can usually be detected from the abnormally low values of capacitance for the high voltage winding. A similar case develops in the low-voltage-to-ground reading of figure 5. The circuit, in such cases, may be composed almost entirely of leakage resistance to ground and may have a high dissipation factor without indicating an abnormal condition.

Measuring Equipment

Available testing equipment for conducting dissipation factor tests is of two general types:

1. Instruments which measure the volts applied, the charging current and the loss.

2. Capacitance bridges which measure the equivalent series capacitance and the dissipation factor.

Table II shows the conversion to equivalent parallel capacitance, parallel resistance, and dissipation factor for each type of instrument. This conversion must be recognized in order to place all data on the same basis of parallel resistance and parallel capacitance.

Results

The results of more than three years of testing have definitely indicated that insulation of low moisture content shows a reduction in its a-c resistance with increasing temperature, the capacity part of the circuit remaining practically constant. For wet insulation, on the other hand, increasing temperature has been found to produce a considerable increase in capacitance as well as a reduction in the a-c resistance.

Dry insulation, therefore, has the highest value of a-c resistance and the lowest value of capacitance. As moisture is absorbed, the first change appears in a reduction of the resistance. Further increase in moisture content at constant temperature increases the capacitance along with a more gradual reduction in resistance.

Figure 6 shows this relation, and the predicted change in dissipation factor, at constant temperature, for varying amounts of moisture.

Figure 7 shows the relation between R and C, for both wet and dry insulation, over the temperature range of 20 to 75 degrees centigrade. This curve is an attempt to show the approximate limits for thoroughly dry insulation and for insulation containing approximately 40 per cent moisture.

Figure 8 shows the relations between temperature and dissipation factor for wet and for dry insulation. It is interesting to note that the dissipation factor for dry insulation increases for increasing temperature faster than for wet insulation. This means that for a known dissipation factor at one temperature, it is not possible to predict what it will be at another temperature, unless the insulation is known to be dry.

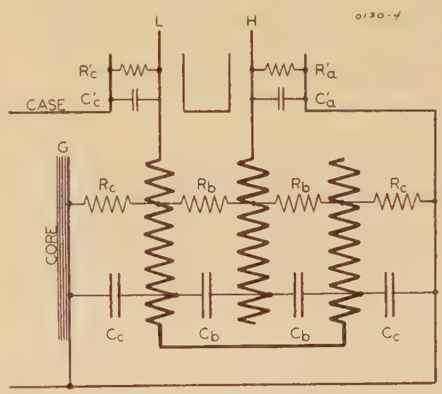
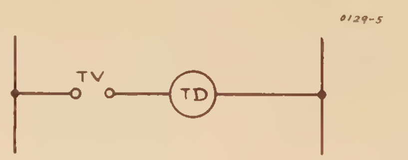


Figure 4. Schematic diagram of a two-winding transformer having core-low-high-low coil grouping



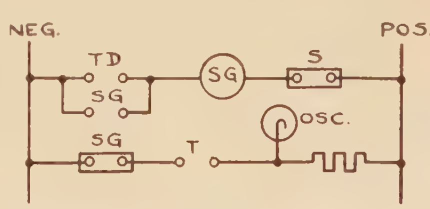


Figure 5. Schematic diagram of a two-winding transformer having core-high-low-high coil grouping

Table II. Conversion to Equivalent Parallel Circuit Constants for 60-Cycle Tests

Method Used	Instrument Reads	R_p	C_p	Dissipation Factor
1. Loss	E, I, and W	$\frac{E^2}{W}$	$\frac{2{,}650}{R_p \times DF}$	$\cot\cos^{-1}\frac{W}{E\times I}$
2. Capacitance bridge	C_s and DF	$\frac{2{,}650}{C_p \times DF}$	$C_s \times \sin^2\theta$	From bridge

Note: Express E in kilovolts, I in milliamperes, W in watts, R in megohms, C in micromicrofarads, θ in degrees (power-factor angle).

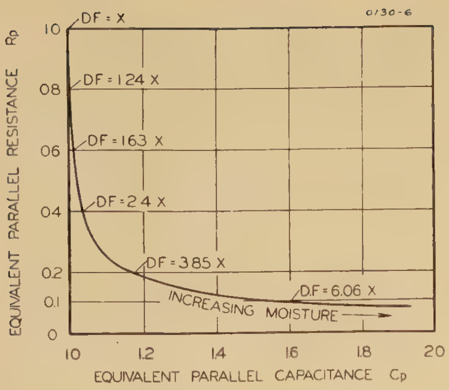


Figure 6. Relation between R_p and C_p for constant temperature and increasing moisture content

Figure 9 shows the changes of R and C for wet and dry insulation as a function of temperature. These characteristics furnish the means for determining the condition of the insulation from the moisture standpoint, since the capacitance component for wet insulation increases much more rapidly than for dry insulation with increasing temperature.

Analysis

To determine the condition of transformer insulation where high dissipation factors are encountered, it is suggested that in addition to the usual checks, such as tests on the oil and Megger tests, dissipation-factor tests be conducted at more than one temperature, and that these tests be separated into the R and C values of the component parts. If the tests do not show an appreciable increase in C for the higher temperature readings, the insulation is relatively moisture free, while if C shows a considerable increase for any one of the separated values, the presence of distributed moisture in that part of the insulation is probably indicated. Corrective measures then consist of either drying the insulation or of reconditioning by other means.

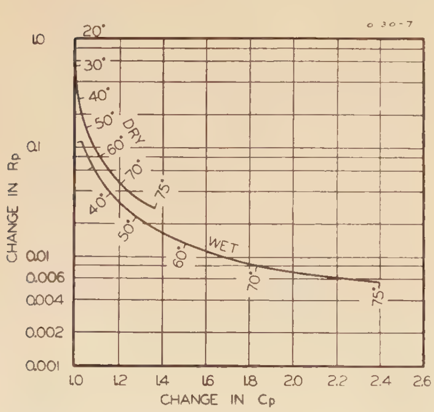


Figure 7. Relation between R_p and C_p for constant moisture content and increasing temperature

Several cases have presented themselves of transformers having high dissipation factors which when tested at two different temperatures did not show an increase in capacitance at the higher temperature. To check this condition, the units were placed in a drying oven for more than 400 hours, part of the time under vacuum. During this time the capacitance did not change and the cause of the high dissipation factor was traced to the transformer oil. When the oil was replaced, the dissipation factor tested normal.

In another case tests conducted on a series of small transformers of the same design, showed variations in the dissipation factor. The winding arrangement of these units was similar to figure 3. When the test results were analyzed all of the variations appeared in the R_b and R_c values, both of which are made up of solid insulation. The R_a value, principally a test of the oil, remained constant. Since these variations were only in the resistance values of the solid insulation, it would indicate slight differences in the drying-out procedure.

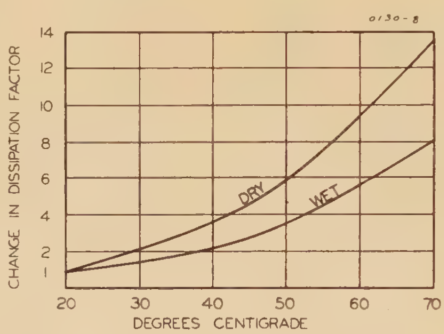


Figure 8. Change of dissipation factor with temperature

An analysis of dry-out runs made in oil have shown, by separating the values, that parts of the insulation sometimes have more moisture in them after the dry-out than they had before, although the over-all dissipation factor was lower. This would evidently indicate a migration of the moisture from one part of the winding to another and that the dry-out run had not been completed.

Cases where the resistance is abnormally low, without a corresponding increase in capacitance, indicate a local low resistance path rather than distributed moisture.

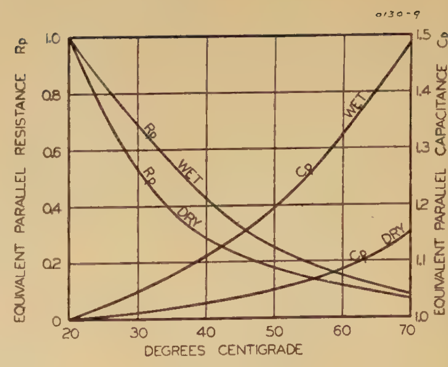


Figure 9. Change of R_p and C_p with temperature

It is recommended that when high voltages are used for conducting these tests, the test voltage be less than the rated voltage of the winding. If higher than rated voltages are used, additional losses, such as for example, the corona loss in the bushings or other parts, may affect the readings and obscure the true condition of the insulation itself.

From this, it is suggested that the results of tests conducted at more than one voltage may be used to detect the presence of corona.

Conclusions

Tests have indicated that when properly applied, dissipation-factor testing, in connection with other accepted tests, may be useful in determining the condition of insulation and sometimes the location of the defective part may be actually determined. It is also possible to determine whether the high dissipation factor is due to moisture or to other cases, which drying out would not improve.

No conclusions have, as yet, been reached regarding the extent to which the resistance may decrease without an appreciable increase in the capacitance before the insulation is considered unsafe from a moisture standpoint. For example: assuming a dissipation factor of X (figure 6), it will be seen that the resistance may drop to 0.4 of its dry value, at the same temperature, with only a slight increase in C, but with an increase to $2.4X$ in the dissipation factor. A change of this order may not be objectionable as it still lies in the vertical part of the curve, indicating only a small increase in moisture content for the higher dissipation factor.

Discussion

Discussion will be found in the 1941 annual Transactions volume and in the June 1941 Supplement to Electrical Engineering—Transactions Section.

Investigation of Starting Requirements of a 660-Horsepower Locomotive Diesel Engine

JOHN C. DAVIDSON
ASSOCIATE AIEE

R. LAMBORN
ASSOCIATE AIEE

PRIOR to 1926 the starting of railway-type Diesel engines was generally accomplished by the use of compressed air. This method of starting had certain disadvantages in locomotive operation, and in an effort to overcome them, a trial installation was made of an electric starting system. This involved the application of a 56-cell lead-acid type storage battery and the addition of a special series winding in the main generator of the locomotive, through which the battery current was passed when starting, causing the generator to function as a series-wound motor. Since that time this method has been used successfully on practically all Diesel-electric locomotives.

Much of the application work in succeeding years was done on an empirical basis; more recently it was felt that a definite analysis of the conditions governing starting should be made on a railway-type Diesel engine. Tests were desired that would permit determination of (*a*) the maximum torque required to turn the engine over against compression, (*b*) the torque and speed at the moment the engine begins to fire, and (*c*) the elapsed time from the closing of the cranking power circuit until the engine begins to fire, for the conditions of a cold, a normally hot, and an abnormally hot engine.

Equipment

The major items of equipment used for the test were an American Locomotive Company 660-horsepower 700-rpm six-cylinder four-cycle, $12^1/_2$-inch by 13-inch Diesel engine, a direct-connected General Electric *GT*-551 traction generator, and a 56-cell *MVMT*-13 Exide Ironclad battery to supply power to the generator for cranking the engine.

Some of the technical difficulties involved in making an investigation of this nature may be readily anticipated, permitting appropriate steps to be taken for their successful solution, while the existence of still other problems may not even be suspected until after a large amount of test data have been worked up and carefully analyzed. The determination of the torque delivered by the cranking motor to the engine, and the engine speed, fall into the former classification.

Because of the pulsating nature of the compression torque of a Diesel engine, it is to be expected that the cranking torque and the speed during cranking will also be pulsating in nature. In the case of a six-cylinder four-stroke-cycle engine, there are three compression strokes per revolution, resulting, at 100 revolutions per minute, in a pulsation frequency of 300 cycles per minute or 5 cycles per second. Recording meters are entirely unsuited for making measurements of this nature because of the high inertia of their moving systems and because of the limitations in the performance of their recording stylus on the chart. The conventional multielement permanent-magnet oscillograph is the ideal measuring and recording instrument for the purpose.

Having determined the necessity of using an oscillograph in the investigation, we must consider what quantities to measure and record. In this respect, the determination of the torque input to the Diesel engine presents the greatest problem. It would be most desirable to determine and record it directly by means of one of the various strain measuring methods, but unfortunately this cannot be done because of the closeness and rigidity of coupling between the generator and engine. In view of this, the most practical method seemed to be the use of the generator itself as a dynamometer. Since it is connected as a simple series-excited motor during the engine cranking period, it is necessary to measure only a single electrical quantity, current input, to permit a quite accurate determination of the torque developed. The few minor loads supplied by the battery while cranking the engine are entirely insignificant compared to its input to the generator; hence the addition of a battery voltage trace to the oscillograph record will permit determination of the battery volt-ampere discharge characteristic. Recording the armature voltage of a small separately excited shunt generator, direct connected to the engine generator set, was chosen as the best and most convenient method of determining engine speed. A 60-cycle voltage wave was also recorded to serve as the basis for all time measurements. Thus, four oscillograph elements were required and arranged to indicate:

A—Battery current
B—Battery voltage
C—Generator speed
D—Time (60-cycle wave)

Test Procedure

Preparatory to the first cranking test, the Diesel engine was warmed up to average operating temperature as indicated by a radiator water temperature of 120 degrees Fahrenheit. Then, after a shutdown of approximately five minutes and at a prearranged signal from the oscillograph operator, the engine starting button was pressed. This start button closed magnetically operated contactors between the battery and the generator, and was held in, maintaining this connection, until the engine was audibly running under its own power. This procedure was followed for each of the four succeeding starts, each time using four cells less of the battery. Oscillograph records designated as tests 1, 2, 3, 4, and 5 in the following tabulations were taken using 56, 52, 48, 44, and 40 cells of battery, respectively.

Following this series of normal-engine-temperature starts, the battery was once more restored to its usual 56-cell connection, and the engine operated under load with radiator fans shut down until an engine water temperature of 180 degrees Fahrenheit was obtained. An oscillograph record designated as test 6 was then taken in the manner described above except that the shutdown preceding the start was of only three minutes instead of five minutes duration, in order to prevent too great a loss in engine temperature, which would have defeated the attempt to obtain the cranking characteristics of the engine while abnormally hot.

Following completion of the day's testing, the water was drained from the engine and radiator system and the

Paper 40-124, recommended by the AIEE committee on transportation, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted April 23, 1940; made available for preprinting May 28, 1940.

JOHN C. DAVIDSON is electrical engineer, American Locomotive Company, Schenectady, N. Y., and R. LAMBORN is engineer, General Electric Company, Erie, Pa.

Acknowledgment is here made of valuable assistance given by D. P. Orcutt of the Electric Storage Battery Company in the preparation of this paper.

locomotive moved out of doors and left to cool down. During the night the outdoor temperature varied between 12 and 22 degrees Fahrenheit. The engine and generator were completely exposed to the wind and weather during this time, as the hood which normally covers this apparatus had not yet been installed. In the morning the locomotive was pushed indoors, the radiator system filled with cold water, and the oscillograph reconnected before proceeding with the cold series of tests. These were made in the same manner as the normal-engine-temperature tests, except 8 cells of battery were cut out between starts, oscillograph records designated as tests 7, 8, and 9 being taken using 56, 48, and 40 cells of battery respectively.

In addition to the oscillograph records, readings were taken from time to time, of radiator-water temperature, lubricating-oil temperature, also battery-electrolyte temperature and specific gravity.

Results

The nine oscillograms taken under conditions as just described have yielded the data shown in table I, which shows the mechanical quantities of torque and speed which these tests were undertaken to determine, also the electrical quantities of amperes (from which the basic uncorrected torque figures are obtained) and volts. Unfortunately, the existence of a calibration error in oscillogram number 1 rendered a portion of its data inaccurate, which accounts for the blank spaces in the tabulation.

The oscillogram of test number 4 reproduced in figure 1 is typical of the records obtained. Various explanatory notes and lines have been added to the original record to aid in tying it in with the values entered in the table of data just mentioned.

However, before attempting a step-by-step interpretation of how the desired information can be obtained from the traces on such an oscillogram, it is desirable to consider for a moment the sequence of events as they take place during the cranking period:

1. As the engine stops preceding the start under consideration, it rocks back and forth several times, finally coming to rest near one of three equally spaced angular positions as determined by the action of the various cylinders which operate in turn as air motors and air compressors.

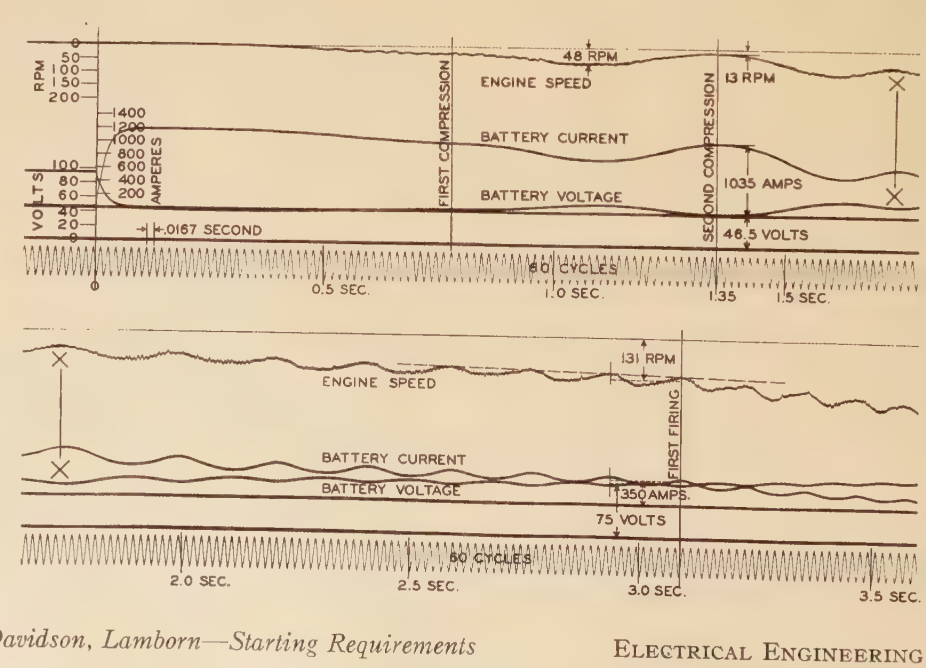
2. From this position of rest, the engine is rapidly accelerated when the cranking circuit is closed. As the first compression stroke will be only a partial one, the maximum compression torque will be less than usual, and the electrical torque of the starting motor may readily be sufficient to continue accelerating the engine as it turns through the position corresponding to the first peak of torque demand.

3. As the first piston goes over dead center, the air motor action in this cylinder aids the starting motor in further acceleration of the engine.

4. As the second compression peak is approached (first full compression stroke), the rotating system decelerates and its stored kinetic energy is released, thus aiding the starting motor. Deceleration must of course cease and acceleration again take place if the engine is to keep on turning over. At this particular instant of zero acceleration, when the rotating inertia effects are zero, the net torque developed by the starting motor is all delivered to the Diesel engine. The tests indicate that this is the maximum torque output required of the starting motor by the Diesel engine at any time during the starting period.

5. The governor and fuel injection system used on this engine are arranged so that a gear pump in the governor must build up a sufficient pressure and flow of oil to operate its power piston before any fuel can be injected into the engine cylinders. Observations indicate that when starting from rest after several minutes shutdown, the engine must turn over approximately three complete revolutions to obtain a fuel rack position equal to that required at idling speed and no load, which corresponds approximately to the minimum charge of fuel which the engine can fire successfully. If the engine speed at the end of three revolutions is sufficient to heat the charge of air undergoing compression to the igniting point of the fuel oil, the engine will start. If the blow-by, slowness of compression, coolness of the engine, or radiation losses are such as to prevent the rise of the combustion air up to the ignition temperature of the fuel by the time three revolutions have been made, additional time, or additional time and cranking speed, will be required before the engine can fire and run under its own power.

Figure 1. Oscillogram showing engine cranking and starting



From the foregoing it should be clear that the observed speed at which the engine first begins to fire does not necessarily bear any relation to the minimum speed at which the engine could fire under the particular temperature conditions. When the engine does begin to fire, its speed rises at an increasing rate with a corresponding change in the rate at which the motor current decreases. This change in rate of decrease of the motor current is found to be the best indication on the oscillograph records of the particular compression stroke which resulted in the first explosion.

The three pulsations per revolution which occur in all the quantities it is desired to measure make necessary the establishment of some arbitrary method of determining their value at the time of firing. For the purpose of this investigation, the average value during the one-third revolution preceding the first explosion will be considered as the value of that quantity at firing.

The conversion of cranking-motor current as read from the battery-current trace on the oscillograms to motor torque is accomplished by reference to figure 2. This is the type of curve sheet commonly prepared to cover the cranking characteristics of a railway-type Diesel-driven generator. In the present discussion, consideration need be given only to the torque-versus-ampere curve. To determine the torque delivered to the Diesel engine at the time of firing, a correction must be made to the value read from the curve to allow for the torque developed by the motor, but which is absorbed internally in accelerating its rotor. The value of this accelerating torque is obtained by first determining the average

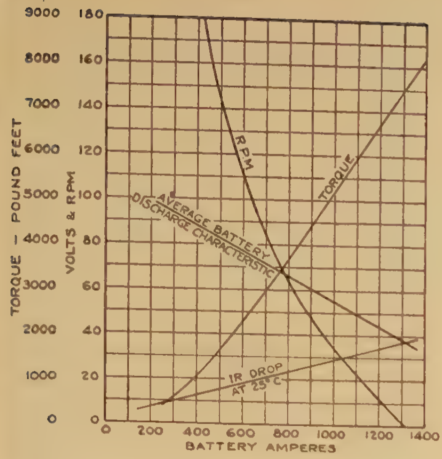


Figure 2. Engine cranking characteristics of GT-551 traction generator with 56 cells of MVA-13 Exide battery

rate of change of speed at the time of firing and applying the formula

$T=K\left(\dfrac{\text{rpm}}{\text{second}}\right)$, where

T = torque in pound feet absorbed by rotor inertia

K = a constant having a value of 12, being in the general case $WR^2\times\dfrac{2\pi}{60\times 32.2}$

$\left(\dfrac{\text{rpm}}{\text{second}}\right)$ = average acceleration at time of firing expressed in revolutions per minute per second

On some of these tests this correction factor turns out to be a very appreciable percentage of the total torque developed by the starting motor.

After this discussion of some of the significant events leading up to the first explosion and a few words regarding the method of determining specific voltage, current, speed, and torque values from the ever-changing values recorded on the oscillograms, we have reached a point where the story told by figure 1 becomes much more understandable.

On this record, time progresses from left to right in the conventional manner. The lower trace is the 60-cycle timing wave, having a time of 0.0167 second between successive upward peaks. Immediately above it is the straight horizontal zero reference line of the battery-voltage element, which shows a maximum deflection corresponding to 95 volts immediately prior to the closing of the starting contactors. The horizontal line immediately above the battery-voltage zero line is the battery-current zero line. Both elements deflect upward for increasing values. However, in the case of the tachometer generator's armature voltage trace at the top of the film, the deflection has been reversed so that a downward trend indicates increased engine speed. Elapsed time measurements will all be referred to the instant that battery current starts to flow.

For convenience, a small amount of overlap has been allowed on the upper and lower portions of the oscillogram as reproduced, the reference line X-X being shown on both portions of the picture. The upper portion shows three compression strokes (one partial and two full) while the lower portion shows 11 compression strokes. Thus the entire record covers approximately $4^1/_2$ revolutions, with an elapsed time of less than four seconds.

The exact location of the peak torque point on the first partial compression stroke is not obvious from a casual inspection of the oscillogram, but may be located accurately by integrating the area between the speed trace and its zero reference line. It will be noted that, following this first compression stroke, the angular velocity of the engine momentarily reaches a value equivalent to 48 rpm, but drops back to 13 rpm at the maximum torque point of the first full compression stroke. At this instant the record shows the battery voltage to be 46.5 volts, and the current 1,035 amperes, with 1.35 seconds elapsed time. By referring to figure 2 we find 1,035 amperes corresponds to 5,450 pound-feet torque.

Having passed over the maximum torque point of the first full compression stroke, the torque required for succeeding compression strokes is, as indicated previously, materially reduced by virtue of the energy recovered from the expansion of the air previously compressed. Because of the series motor characteristics of the starting motor, the system accelerates quite rapidly, with a relatively uniform dropping off in current. A smooth curve drawn through the peaks of the current trace shows a decided break following the ninth full compression stroke. Thus it is on the ninth full compression stroke or approximately 3.1 revolutions from rest, and after 3.10 seconds elapsed time, that the first explosion took place. Although the starting contactors were held closed for approximately 0.9 second after this first explosion, they could have been opened sooner, and the engine would have continued to run under its own power, accelerating up to the idling speed for which its governor was adjusted.

Averaging the traces of the current, voltage, and speed elements for the one-third of a revolution preceding the time of firing gives values of 350 amperes, 75 volts, and 131 rpm, corresponding to the figures appearing in table I. The average current of 350 amperes corresponds to 790 pound-feet torque as read from the curve of figure 2. As previously explained, this must be corrected for the torque used in accelerating the generator armature. A line drawn to represent the "average" speed of the engine prior to firing has a slope corresponding to approximately 24 rpm per second. Applying the formula $T=12$ (rpm/second) results in a value of 290 pound-feet for the average armature accelerating torque. It is only the difference between 790 pound-feet and 290 pound feet, or 500 pound-feet of torque, that is available for cranking the engine.

Conclusions

In 1930, when this particular size Diesel engine was first being applied to railway

Table I. Summary of Information Obtained From Oscillograph Tests

Battery: Number of Test	Battery: Number of Cells	Temp. of Circ. Water (Deg F)	At Second Compression: Battery Volts	Battery Amp	Torque (Lb Ft)	Speed (RPM)	At Firing Speed: Battery Volts	Battery Amp	Torque (Lb Ft)	Speed (RPM)	Elapsed Time (Sec)	Revolutions to Fire
1	56	120	56			33	96			171	2.72	3.8
2	52	120	57	1,050	5,600	30	88	420	800	138	2.42	2.8
3	48	120	53	1,040	5,500	25	80.5	410	900	130	2.76	3.1
4	44	120	46.5	1,035	5,450	13	75	350	500	131	3.10	3.1
5	40	120	41.5	1,030	5,450	0	67	355	600	106	4.66	2.8
6	56	180	55	1,290	7,400	10	98	400	600	169	2.67	3.2
7	56	56	57.5	1,040	5,500	21	82	565	1,800	101	2.72	3.1
8	48	53	44.5	1,100	5,970	8	70.5	540	1,500	93	3.00	2.8
9	40	53	35.5	1,050	5,600	0	60.5	460	1,200	89	5.48	3.8

use, its cranking requirements were given as 4,500 pound-feet breakaway torque and 1,500 pound-feet torque at 140 rpm firing speed. An equipment designed to meet these specifications was found inadequate, and in 1931 the requirements were altered to 6,400 pound-feet breakaway torque and 1,500 pound-feet torque at 80 rpm firing speed. As a result of these tests, it seems that the cranking requirements of the engine are still understated, and that at least 7,000 pound-feet torque at standstill and at least 2,000 pound-feet torque at 80 rpm firing speed should be provided. The excellent service record of the electrical cranking equipment used on these engines during the past eight years is most certainly due in part to the leeway provided by the manufacturers over the engine builder's stated requirements. It may be of interest to compare the torque rating of this engine, which is 4,952 pound-feet, with the 7,000 pound-feet or more of cranking torque required under certain conditions.

Past practice in applying electrical starting to Diesel engines has universally been based on the assumption that the breakaway torque of the cold engine represented the maximum torque requirement. This series of tests indicates that the torque required to turn a hot Diesel engine through its first full compression stroke may exceed that necessary for all other operating conditions. While no true breakaway torque requirements of this engine were obtained, the ease with which it started on test number 7 and the accumulated service experience on a large number of similar equipments tends to confirm this new point of view. Aluminum pistons were used in the engine under test. It is to be expected that the use of cast-iron pistons might materially change starting conditions.

Electrical equipment for engine cranking could most certainly be more efficiently designed and applied if additional information on the actual starting requirements of large Diesel engines were available. Special caution must be used if an attempt is made to apply data derived from these tests to other large engines differing from it as regards number of cylinders, size of cylinders, or combustion cycle.

Discussion

Discussion will be found in the 1941 annual TRANSACTIONS volume and in the June 1941 SUPPLEMENT to ELECTRICAL ENGINEERING—TRANSACTIONS SECTION.

The Application of Electricity for the Auxiliaries of Railroad Trains

J. E. GARDNER
MEMBER AIEE

Synopsis: Although the application of electricity for the auxiliaries of railroad trains has not been as spectacular as its use for traction purposes this has increased in a remarkable manner since its first application for electric-lighting purposes about 60 years ago.[1] This application was confined largely to lighting purposes until the last few years when streamlined high-speed passenger trains and air-conditioned cars have ushered in a new era of railroad transportation. This paper points out the increased use of electricity for auxiliaries other than those in electric and Diesel-electric locomotives.

First Uses of Electricity on Cars

THE earliest applications were for lighting purposes only and were of the following systems:

First. The head end system, consisting of a steam engine generator or steam turbogenerator, together with several sets of storage battery. This furnished lights to an entire train.

Second. The axle-generator system, consisting of a generator belted to one of the car axles, combined with a storage battery. This furnished lights to the individual car on which it was applied.

Third. The straight storage system, consisting of several storage batteries on a train, the batteries being charged at terminals.

In addition to these, numerous other experiments were tried, even including a windmill-driven generator attached to the front of a steam locomotive.

Head-End System

The "first" method was called the "head end" system of lighting, so called due to the turbogenerator being located in a baggage car at the head end of the train. With the head-end system several storage batteries were distributed in the train and the nominal voltage was either 110 or 64 volts. The generator was operated at scheduled times with most of the battery charging done in the daytime to prevent excessive lamp burnouts due to overvoltage or else an adjustable resistance was used in the lamp circuit during charging periods. Cars were equipped with an overhead train line consisting usually of three 4/0 cables with two of the cables cross connected at the rear of the train in order to give more uniform lighting voltage throughout the train by means of a three-wire loop system.

In earlier head-end installations a generator of about 25-kw capacity supplied energy for electric lights and battery charging for an entire train but the advent of air conditioning has increased the electric load to such an extent that electric lighting is now only a minor part of the total electric load.

Some of the shorter Diesel-driven streamlined trains use a nominal 64-volt generator belted to the main Diesel engine but the longer trains use one or more auxiliary Diesel-engine-driven alternators which furnish 220-volt 60-cycle three-phase power for the train. This voltage was used as 220 volts has been adopted by the American railroads as the standard a-c voltage for station and coach-yard standby connections for air-conditioned cars.

However, especially where a certain amount of electric heating is used, this voltage necessitates unusually heavy train lines so that for trains of more than 10 or 12 cars a higher voltage would be more economical. The next step would be to 460-volt three-phase generators or, if much electric heating is used on the train, 2,300-volt three-phase generators would undoubtedly prove more economical.

This use of head-end power is feasible only with articulated trains or others that are operated as a unit and on account of the increased flexibility the greater number of passenger cars have their own individual axle generators and batteries. As a result the head-end system has been abandoned for other trains with the exception of certain suburban trains where the turbogenerator is located on the locomotive. The usual practice on such suburban trains is to omit the storage batter-

Paper 40-123, recommended by the AIEE committee on transportation, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted April 18, 1940; made available for preprinting May 31, 1940.

J. E. GARDNER is electrical engineer, Chicago, Burlington, and Quincy Railroad Company, Chicago, Ill.

1. For all numbered references, see list at end of paper.

ies and operate the turbogenerator whenever any lights are required in the train.

Axle Generators

For non-air-conditioned cars the axle generators have generally been of from two to four kilowatt capacity, using 32-volt batteries of from 250 to 350 ampere-hour capacity.

For air-conditioned cars axle generators, 15 and 20 kw capacity, are in common use with electromechanical air conditioning systems, with 1,000-ampere-hour batteries at 32 volts, almost the minimum size. A nominal voltage of 32 is in general use although certain roads are using 64 volts to reduce the size of cables and other current-carrying equipment.

For the smaller axle generators, such as four kilowatt, flat rubber belts have been the general standard although a number of vee belts and a few chain drives are in use. For 15- or 20-kw axle generators either gear drives or combination vee-belt and gear drives are universally used, the large majority of the generators being suspended from the body of the car and driven through splined propeller shaft. However, a number of generators are truck suspended and driven either by vee belts or spur gears.

Successful air conditioning of cars has been much more difficult than air conditioning of buildings due to the low narrow rooms, the limited space available for equipment, and the limited power supply. Much care has been used in developing air-conditioning control and air distribution in order to provide better temperature conditions and to reduce objectionable drafts.

Power Supply for Air Conditioning

Various methods are used to drive the Freon compressor when the Freon compression system of air conditioning is employed.

One system uses a d-c motor, often in the same frame with a 220-volt three-phase motor for station or yard use.

In a second system the compressor is driven from the axle through an electric slip clutch which limits the compressor to a predetermined maximum speed. Here again an electric motor is often added to take over the compressor load automatically whenever the car speed is low or the car is standing still, this motor being sometimes so controlled that it becomes a generator when the car speed reaches a certain point, thus making a separate axle generator unnecessary.

A third system uses an automatically controlled propane-gas engine for driving the compressor.

The first two of these systems of course, take power from the locomotive to operate the compressor whereas the third system does not.

Two other systems of car air conditioning are in general use, one being the steam-jet system using steam from the locomotive and the other the ice-activated system. All systems use electric motors for driving blowers and fans inside the car, the steam-jet system uses them for pumps and condenser fans, and the ice-activated system for the ice-water pump.

Use of Diesel and Propane-Gas Engines

Four cars have been equipped with individual Diesel-engine-driven alternators which furnish power for air conditioning, lighting, electric heating, etc. Here hot water from the Diesel-engine jacket water system is also used for heating, no steam heat being used. The Diesel engine and alternator are mounted on a sliding carriage so that they can be pulled out for convenient maintenance. When in normal position they are enclosed in a steel box to quiet the engine noise. The Diesel engine is operated whenever the car is in service. The engine is started and stopped by push buttons located inside of the car and generator voltage regulation is entirely automatic. The transition between car heating and car cooling is also performed automatically.

One or more cars have been equipped with a Diesel engine driving both an air-conditioning compressor and an electric generator.

A number of cars have also been equipped with an automatically controlled propane-gas engine generator set, the majority of these being on cars using a propane-gas engine for air conditioning also.

Locomotive Lighting

In contrast with the large increase in the electric load of passenger cars the electric load of modern steam locomotives is really less than it was on the earlier installations. This is due to the higher efficiency of incandescent headlight lamps over that of the arc headlights which were used at first. A 250-watt headlight is the usual size and a steam turbogenerator with a capacity of 500 to 1,000 watts at 32 volts direct current is quite generally used as the source of power supply.

The addition of train-control equipment has increased the electric load on locomotives equipped with this but this increase has been less than the decrease due to the substitution of incandescent lamps for arc lamps.

Progress in Car Equipment

The improvements that have been brought about in the art of supplying electricity for car use have been primarily to supply more reliable power and second to supply enough power in recent years to meet the ever-increasing demands.

Axle generators and their control were improved year after year as experience brought out their weak points. Moving parts of voltage regulators were counterbalanced to protect them from sudden movement of the car, flat belts and pulleys were improved to give the belts longer life and prevent excessive belt slippage in freezing weather. Vee-belt drives and gear drives were developed to give more positive driving conditions with larger power requirements. Voltage for lights and certain motors and control has been made more uniform through lamp-voltage regulators of the carbon-pile type. Thermostatic temperature regulation is now practically universal for air-conditioned cars, both for heating and cooling.

Electric lighting in cars is being constantly improved and higher intensity provided. Lighting fixtures have been improved, perhaps occasionally with more regard to artistic lighting than to furnishing the proper intensity efficiently.

Indirect lighting has been used in many cars with good results. Lenses of both the prismatic and the "bull's eye" type are being used on lighting fixtures to distribute the light properly. Night lighting has advanced from reduced-voltage dimming arrangements to the use of small auxiliary blue lights and the occasional use of under-seat aisle lights. Many coaches now have reading lights on the lower side of the bag racks, individually switched at the passengers' will. Sleeping-car berth lights have been decidedly improved recently and special attention has been given to mirror lighting in dressing rooms. Electric lamps are of course, being continually improved and today a number of special lamps are used where the type of fixture requires it.

Fluorescent-lighted cars appeared in 1939 and a number of them are now in service. The effect produced by fluorescent lighting is good as well as novel and these lamps offer a means of improving the lighting of cars due to their high efficiency. Due to the limited amount of

electricity available on passenger cars it has always been more difficult to furnish good lighting on cars than it is in buildings, consequently any improved light source is welcomed by car lighting engineers. However, with the exception of the few cars equipped with a-c generators, the common use of low-voltage direct current for car lighting has complicated the use of fluorescent lamps and made their over-all efficiency lower than it would be were a-c power available. In some installations a small motor-alternator has been used to provide the a-c power and in others a number of small vibrators have been used. Now the lamp manufacturers have introduced fluorescent lamps and auxiliaries that will operate on 64 volts direct current. One or more test installations have been made and where this voltage is available it is unnecessary to convert it to alternating current.

Ten years ago 700 watts was an average electric load for a railroad coach whereas now 2,500 watts is not considered excessive for lighting in addition to an air-conditioning load of around ten kilowatts. In other words it is not unusual for a present day coach to have over 16 times the electric load of a coach ten years ago while the addition of modern dressing and smoking rooms has decreased its passenger-carrying capacity.

There have been a few installations of electric refrigeration on dining cars but their use has not been extended as refrigerators must be kept in service when the car is standing in the coach yard between trips and this involves a serious drain on the car battery. Electric drinking water coolers are however, now frequently installed.

Electric cooking equipment is used on a small scale, that is for grilles, toasters, coffee makers, etc., but so far as we are aware there has been no completely equipped dining car as the electric range and electric water heaters would have a connected load of about 87 kw and the cost of providing power for such a load is not warranted. Consequently coal in some form is still the usual fuel for cooking, with a few installations of oil and of propane gas.

Some recent dining cars however, have motor-driven blowers to furnish draft for the range and have electric dish washers and garbage grinders.

Other miscellaneous electric devices on modern cars are radios, either a-c receivers with a motor generator set or inverted rotary converter or else a-c receivers of the automotive type. In fact radios have been in common use on the western roads for over ten years and a few are in use in the east.

In a number of cases one receiving set operates loud speakers in other cars or even on an entire streamlined train and there are a number of installations of radio-phonographs.

The introduction of electric razors has caused a demand for 110-volt a-c outlets in dressing rooms. This voltage has generally been obtained by the use of vibrating inverters.

The need of improved air brakes for high-speed trains has caused the use there of electric control in connection with the air-brake system. With such control the brakes can be applied at the same instant on every car in the train. Automatic track-sanding devices and devices to prevent wheel sliding with heavy brake applications are sometimes added.

This equipment does not require much electricity for its operation but does necessitate much additional wiring and equipment on the train.

Station and Coach-Yard Facilities

Station and coach-yard requirements have naturally been greatly increased due to the increased use of electricity on cars. Battery-charging facilities at terminals have always been necessary with axle-generator cars. Formerly the capacity of such battery-charging plants was determined by the needs in adverse winter weather when batteries would become exhausted due to excessive belt slippage.

The present use on air-conditioned cars of batteries having a capacity three or more times than formerly used has changed the heavy battery-charging season to the hot summer season and in many cases has made the former facilities inadequate.

As the majority of cars air conditioned with the Freon compression system have 220-volt three-phase motors for use in terminals this has required many installations there of a-c receptacles, each with sufficient capacity to furnish power for a 15-horsepower motor. Incidentally this motor frequently operates the d-c compressor motor also as a generator to furnish sufficient direct current to carry the blower motors, electric lights, etc., on the car.

To avoid the expense of installing additional high-capacity battery-charging circuits at a terminal already equipped with a-c receptacles, portable motor generator sets or rectifiers are in quite common use. Generally these are enclosed units mounted on rubber-tired wheels so that they can be moved to the side of a car when needed. A line of small portable gas-engine-driven generators is also on the market for use where a-c power is not available.

Passengers will undoubtedly continue to demand higher intensity of electric lighting in passenger cars just as they continue to use higher intensity in their homes and offices.

Conclusion

A recent committee report of the Association of American Railroads[2] estimates the possible total load of a railroad car as follows:

Lighting, etc.	5.0 kw
Air conditioning	10.0 kw
Overhead heat	15.0 kw
Water heating	10.0 kw
Battery charging	5.0 kw
Total	45.0 kw

With steam as the common source of heating for passenger cars there is not likely to be much electric heating used, especially on cars equipped with axle generator so that the committee report is undoubtedly correct in predicting that 30 kw is undoubtedly the limit to the size of future axle generators.

References

1. Report of Committee on History of Railway Electric Train Lighting, **Patrick Kennedy**, committee chairman. Transcript of *Proceedings* of the Association of Car Lighting Engineers, first annual convention, 1908, pages 23–5.

2. Report of Committee on Car Electrical Equipment, **L. J. Verbarg**, committee chairman. 1939 *Proceedings* of the Association of American Railroads, Electrical Section, Mechanical Division, pages 125–213.

Discussion

Discussion will be found in the 1941 annual Transactions volume and in the June 1941 Supplement to Electrical Engineering—Transactions Section.

A New High-Speed Thermal Wattmeter

JOHN H. MILLER
MEMBER AIEE

Synopsis: The thermal converter discussed in this paper is of the type which produces at its output terminals a millivoltage proportional to the polyphase power connected to its input terminals, the connections being made as for a wattmeter. High-speed response is secured through the use of a new circuit network wherein the thermocouples function also as heaters. Response time of the order of one-half second is obtained. The use of nickel-alloy transformer cores saturating at overloads broadens the overload capacity of the thermal unit itself. Thermal converters of this type are widely used in the summation of power.

THE measurement of various electrical quantities through the medium of heat has intrigued engineers for many years. Instruments indicating through the mechanical expansion of an electrically heated member were among the very first available to the engineer. However, difficulties in compensation for ambient temperature changes and the lack of perfectly elastic materials at the higher temperatures have caused such devices to be replaced by others not subject to such deficiencies.

The thermal ammeter, with a conventional, permanent-magnet moving-coil movement actuated by the potential developed by a thermocouple in thermal contact with the heated member, has no such inherent disadvantages and may be completely compensated against the effect of ambient temperature variations. Through the use of noble-metal alloys for heater and couple, long-time stability is assured. Such instruments are considered as standard for the measurement of current at frequencies above the conventional design range of electromagnetic devices. Mention should also be made here of thermal converters in vacuum for low currents and those having thin tubular heaters for heavy currents at the higher frequencies, all expanding the range of usefulness of the general principle. Through the use of suitable low-range thermal instruments of this type and series impedances of suitable characteristics the accurate measurement of potential becomes possible even at the higher frequencies.

Theory

The measurement of power through thermal means is nearly as old as the measurement of current. Two heated units are used, one of which is heated by the algebraic sum of two derived currents and the other, by their difference. One of the derived currents a, is in phase with and proportional to the circuit current; the other, b, is in phase with and proportional to the potential. The current in one heater is then

$$\sqrt{a^2+2ab \cos \varphi+b^2}$$

and in the other is

$$\sqrt{a^2-2ab \cos \varphi+b^2}$$

where φ is the phase angle between current and voltage. The quantity of heat produced in the two heaters, assuming the resistance to remain constant, is I^2R, or

$$R(a^2+2ab \cos \varphi+b^2)$$

and

$$R(a^2-2ab \cos \varphi+b^2)$$

respectively. This heat is lost largely by conduction and convection with very little lost by radiation, all by reason of heater design. Goodwin,[16] shows that under such conditions, and for the relatively small temperature rise of less than 200 degrees centigrade used here, the temperature rise of the heated member is very closely proportional to the quantity of heat produced in it. If an indication can be obtained proportional to the *difference* between the temperature of the two heaters, the squared terms cancel, and an indication results proportional to $4R\,ab \cos \varphi$, or to power.

The derived currents are usually obtained through transformers. Current transformers of conventional design or modified to meet circuit requirements may be used. Potential transformers are also required to give a current in the network which is a function of the true voltage but of the same order of magnitude as the full-load current from the current transformer for optimum operation of the thermocouple heater combination. Resistance in the potential circuit may be added in the primary or secondary for adjustment and to maintain the derived current truly representative of the potential.

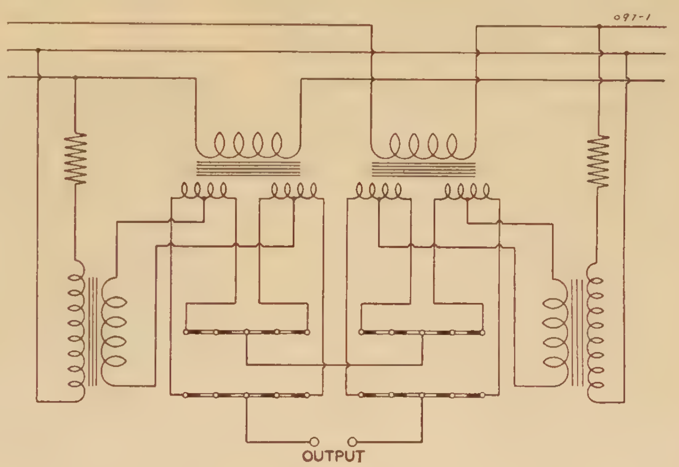


Figure 1. Complete schematic circuit of polyphase thermal converters

Prior Devices

The Lincoln demand meter functions on this principle, the deflection of thermally responsive bimetallic spirals associated with the two heaters and coupled in opposition giving the final indication. Another form of device disclosed by Lincoln,[15] and functioning on the difference of pressures developed in hydrostatic chambers associated with the heaters is representative of another method of securing the mechanism for indicating a temperature difference. Both of these methods are slow in response because of the relatively great thermal capacity of the systems and find their greatest field of usefulness in the art of demand metering where their inherent slow logarithmic response is useful.

The use of thermocouples thermally connected to the two heaters and con-

Paper 40-97, recommended by the AIEE committee on instruments and measurements, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted November 15, 1939; made available for preprinting May 3, 1940.

JOHN H. MILLER is assistant chief engineer of the Weston Electrical Instrument Corporation, Newark, N. J.

16. For all numbered references, see list at end of paper.

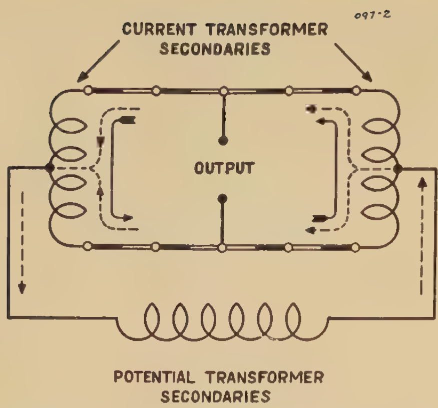


Figure 2. Schematic diagram of transformer secondaries and thermocouples in one phase

nected in opposition to a d-c millivoltmeter was appreciated early in this development as indicated by a drawing in one of Lincoln's patents. The idea was further developed into commercial form some years ago by Perry Borden and H. S. Baker in collaboration with engineers of the Lincoln Meter Company of Canada. This converter, however, is rather slow in response largely because of the mass of the heater units, the surrounding structure, the couple insulation, and the total length of the group of couples. For demand metering this was satisfactory, and the slow response mitigated against burn-outs on heavy overloads, again due to sheer thermal lag. As an indication of the order of the time lag, one such converter reaches 90 per cent of its final deflection in 11 seconds or 99 per cent in 22 seconds, practically final deflection. It might also be noted that the internal resistance of the d-c millivolt circuit has generally been high, of the order of 35 ohms.

For polyphase power, two such systems may have their d-c millivolt outputs connected in series to give an output which is a function of true three-wire polyphase power and for three-phase four-wire service, three single-phase systems may have their output added. For totalizing power in independent systems which may or may not be in phase or, indeed, of the same frequency, the millivolt output of several polyphase converters may be added, with the input to the several units isolated by means of transformers.

The New Device

In the practical application of prior devices the slow speed of response has frequently prevented proper records or indications of phenomena acting at a moderately rapid rate. With a response time for 90 per cent of 11 seconds, only rather slow changes can be shown. Occasionally there have been requirements for much more rapid response, of the order of one or two seconds, which were simply impossible of attainment because of the inherent lag in the produced direct potential. A device with much more rapid response was, therefore, indicated as being most desirable and quite essential for the indication of material system power changes happening within a few seconds.

Another difficulty with the prior devices is their relatively high resistance. While largely used for totalizing in conjunction with potentiometer-type indicating or recording devices, in some instances simple indicating instruments are deemed suitable for the application. However, with the normal output of 50

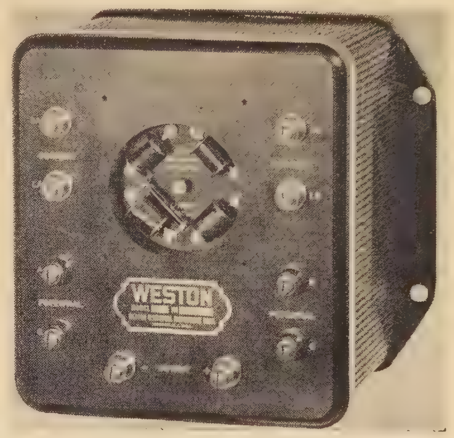


Figure 3. Assembled thermal converter with plate removed showing resistors for field adjustment

millivolts at full rating of the prior devices, with an internal resistance of 35 ohms a maximum of only 18 microwatts could be supplied to an instrument. Even though several such units were totalized, the energy is still very small if it must be transmitted over any considerable length of line. It was indicated, therefore, that a new device should have a much lower internal resistance as respects the output circuit, and, if practicable, a higher millivolt value. As evidence that this has been accomplished, the new thermal converter produces 100 millivolts with an internal resistance in the millivolt circuit of 1.8 ohms so that 1,400 microwatts may be taken from it at full rating. This increase of about 75 to 1 in total output to the indicating or recording device, allows for the use of indicating instruments with better performance characteristics over considerable line lengths; the device will also actuate a direct-writing d-c recording instrument although not at any great distance.

The two desirable features of more rapid response and lower resistance would seem to be possible if the thermocouples and heaters could be more closely associated to secure better heat transfer; the mass of the thermocouples might then be reduced and the resistance of the couples themselves also materially lowered.

In all of this preliminary study it was also obvious that the overload capacity was important and should not be reduced in the improved design. Disregarding for the moment the apparent inconsistency of rapid response and high overload capacity, it is obvious that for a short time constant the heaters and associated thermocouples must be made small in mass. Such heater and thermocouple assemblies as used in ammeters, with temperature compensation, would serve except for the fact that in these the couple is welded directly to the heater, and in the conventional, previously used circuits for watt converters these welds would result in cross-connected short circuits. While couples have been attached to heaters with insulation between, the assembly is usually difficult and fragile if reasonable response speed is obtained.

The Circuit

A study was therefore initiated as to the possibility of using conductively connected couples and heaters and evolving a suitable circuit network. Figure 1 shows such a circuit where the thermocouples proper also act as heaters, somewhat as in the bridge-type converters for

Figure 4. Interior assembly of polyphase thermal converter

thermal milliammeters. The thermocouple wires shown solid are of one material, those in outline of another alloy. The wires are of the same size and the same resistance, but their thermoelectromotive force is considerable with respect to each other. The small circles represent the studs to which the couples are attached and which function as the cold ends of the thermocouples, being bolted to a heavy brass plate with thin mica insulation. This arrangement gives excellent heat flow from the studs to the brass plate which serves as a thermal base line. The temperature rise of the thermo junctions between these studs, above the temperature of the studs and the brass plate, is a direct function of the I^2R loss in them, and without regard to the ambient temperature. And the millivoltage produced by each thermo junction is also a direct function of the I^2R loss except for the slight curvature of less than one per cent in the millivolt versus temperature relation of the materials selected and over the temperature range actually used.

For simplicity in the schematic diagrams, two couples only are shown on each side or a total of eight in all for one phase; in the final polyphase device to obtain the full 100 millivolts, a total of 40 couples are used, 20 in each phase with 5 in each of the four legs of the bridge. It should be noted that the thermally produced potentials of the several couples in each arm are truly additive since each couple is brought back to a pair of studs representing the cold ends with the center junction at a higher temperature.

Figure 2 shows a schematic diagram of the transformer secondaries and couples alone of one phase only, and it will be noted that the output terminals are symmetrical and at zero alternating potential with respect to each other from either transformer. The upper set of couples carries the sum of the two currents and the lower, the difference; hence, the upper set will be at a higher temperature than the lower. If the couple wires change materially in resistance, that is, have a high temperature coefficient of resistance, the current from the potential transformer will no longer be divided equally in both branches. This, however, may be largely prevented through the use of alloys having low temperature coefficients of resistance as compared with the coefficients of pure metals.

Analyzing the circuit with respect to the current transformer, it will be noted that, for a given primary and secondary current, the net secondary ampere turns remain constant irrespective of the value of the current from the potential transformer. The assembly of current transformers with the two independent secondaries, each of which is center tapped, is relatively simple and introduces no difficulties.

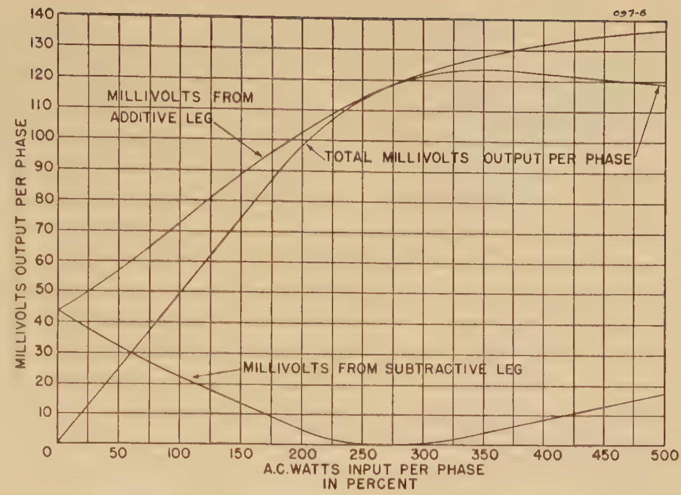


Figure 6. Total millivolts output for one phase and millivolts from additive and subtractive groups individually

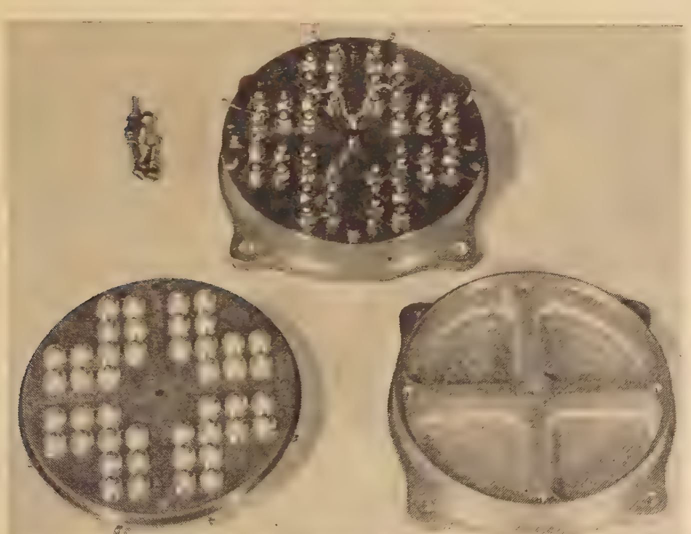


Figure 5. Details of the thermocouple group

General Description

Such an assembly, using thermocouples operating at around one ampere, has a very fast response and will actually come to 99 per cent deflection in 0.5 second. However, this fast response would make the assembly particularly vulnerable to short-time overloads when used in a power plant or in a power system for totalizing.

Recourse has, therefore, been had to the use of nickel-iron alloy cores (Hypernik, Permalloy, Mumetal), all of which have a high permeability at low densities but which saturate quite rapidly thereafter. Such materials, if used for cores in current transformers and where toroidal lamina are used without joints, will allow for the design of current transformers which are amply accurate for the purpose, both as to ratio and phase angle, from no load to full load, with a very small drop for full load at 50 per cent power factor and thereafter will saturate rapidly and give a high degree of protection against overload. This, of course, is predicated on a fixed load and a fixed frequency; the fixed load in this instance is the thermocouple converter proper, and the device can be designed for the frequency with which it will be used. The final design has been so proportioned that the current transformer will be within one-half of one per cent of the five-ampere value up to five amperes primary current, will be within two per cent at ten amperes as representative of low power factor and at higher currents will rise very slowly.

Figure 3 shows an assembled polyphase Thermoverter and figure 4 shows the interior assembly. The toroidal nickel-iron-alloy-core current trans-

formers which are of rather small size are contained in a molded housing back of the thermocouple assembly proper. The conventional shell-type transformers seen in the lower part of the figure are the potential transformers for the two phases; just above them on each side are the conventional wire-wound mica sheets serving as the series resistance in the potential circuits.

Figure 5 shows details of the thermocouple group. The thermocouples, which function also as the heated members, are of noble-metal alloys and are soldered to the relatively heavy studs as can be noted. The chamber on which the plate is mounted contains four chambers so that the heated air in the A-phase summation group for example, does not circulate in the portion containing the subtraction group and raise its temperature. This construction minimizes position errors although these are still of the order of one per cent from vertical to horizontal position, and the device should be mounted in a vertical plane as calibrated.

At full load, 500 watts per phase at 115 volts, the potential losses are about 7.4 watts for 7.5 volt-amperes and 0.8 watt for 0.8 volt-ampere in each current circuit. The output is 100 millivolts from a circuit having a resistance of 1.8 ohms.

Figure 6 shows the millivolt output of a single phase plotted against per cent load as well as the individual millivolt values from the addition and subtraction groups. Note that the subtraction group gives a millivolt value going through zero and again rising, this applying only at unity power factor. At other power factors this value will not go to zero, but the total millivoltage will still be truly representative of the total power.

Field Adjustments

The four small resistance units which are normally covered by a plate serve for field adjustments. The two upper spools are in series with the potential-transformer primaries and will allow for about five per cent adjustment of total output. The lower spools form a potentiometer system so that a fixed proportion only of the total output may be taken from the output binding posts. This is of importance in the summation of the output of a group of thermal converters where the millivolt output of each must represent a definite ratio to the primary power; with different transformer ratios the output millivolts of each unit may be so adjusted that the true summation of power is had. It should be pointed out that with this arrangement the effective output resistance from the converter is increased, and summation must be by some means drawing no current as with an automatic recording potentiometer.

Accuracy

An accuracy of better than one per cent of full-load output, 100 millivolts, is had up to 125 per cent of full-load volt-amperes; up to 200 per cent full-load volt-amperes the error is less than two per cent, again in terms of the 100-millivolt output. It should be noted that the errors at the higher volt-ampere loads are not power factor errors as such but are evidence of the beginning of saturation in the current transformers. At zero power factor the output is zero and at 50 per cent power factor no discernible power factor error as such exists.

No claim is made to high precision in a device of this sort. The effort has been rather to produce a device of moderate accuracy for use in totalizing and in conjunction with switchboard instruments with ample output and inherent overload protection.

Conclusion

With a d-c millivoltmeter connected to the output of this new converter, and a conventional polyphase wattmeter in series with the converter to a rapidly varying load, it is interesting to watch the more rapid response of the d-c instrument and converter as compared to the conventional polyphase wattmeter.

The combination of rapid response and low output resistance would indicate a larger field of usefulness for the thermal watt converter.

Bibliography

1. United States Patent 425,269, April 8, 1890, Milton E. Thompson.

2. British Patent 15,618, 1897, M. B. Field.

3. German Patent 11,721, 1899, R. Bauch.

4. British Patent 2,948, November 4, 1904, William D. B. Duddell.

5. French Patent 435,290, February 26, 1912, M. E. Fauvin.

6. United States Patent 1,156,412, October 12, 1915, P. M. Lincoln.

7. Rates and Rate Making, P. M. Lincoln. AIEE Transactions, volume 34, October 1915.

8. United States Patent 1,199,444, September 26, 1916, Thomas W. Varley.

9. British Patent 119,388, 1918, E. Fawsett.

10. United States Patent 1,765,563, June 24, 1930, Perry A. Borden, H. S. Baker, and L. A. Paine.

11. E. Fawsett, *Electrician* (London), volume 88, January 20, 1922, page 71.

12. The Character of the Thermal Storage Demand Meter, P. M. Lincoln. AIEE Transactions, volume 37, 1918, page 189.

13. Totalizing the Load of Four Stations, Perry A. Borden, *Electrical News* (Toronto), volume 35, December 1, 1926, pages 35–8.

14. Totalizing of Electric System Loads, P. M. Lincoln. AIEE Transactions, volume 48, 1929, page 775.

15. Improved Electrothermic Instrument, P. M. Lincoln. Electrical Engineering (AIEE Transactions), 1935, page 474.

16. The Compensated Thermocouple Ammeter, W. N. Goodwin, Jr. Electrical Engineering (AIEE Transactions), 1936, page 23.

Discussion

Discussion will be found in the 1941 annual Transactions volume and in the June 1941 Supplement to Electrical Engineering—Transactions Section.

Transactions Section

Preprint of Corresponding Pages From the Current Annual Transactions Volume

Any discussion of these papers will appear in the June 1941 "Supplement to Electrical Engineering—Transactions Section"

A Comparison of the Relative Efficiency of the Schafer and Pole-Top Methods of Artificial Respiration

W. B. KOUWENHOVEN
FELLOW AIEE

D. R. HOOKER
NONMEMBER AIEE

O. R. LANGWORTHY
NONMEMBER AIEE

THE pole-top method of artificial respiration was devised by E. W. Oesterreich[1] of the Duquesne Light Company, Pittsburgh, Pa., to give prompt aid in case of electric shock occurring while men are working on poles of power lines. When a worker receives an electric shock while working on a pole minutes elapse before he can be lowered to the ground and resuscitation started by the prone-pressure method. In the field, the elapsed time is seldom less than five minutes[2] and in many cases it is considerably longer. The pole-top method of resuscitation was developed to reduce this period. Tests have shown that an operator can reach a man working alone on a pole and start squeezing his abdomen within approximately one minute.[2] If there are two men on the pole and one receives a shock the elapsed time before the first pressure is applied is much shorter. While an operator is applying the pole-top method, other members of the line crew make preparation for lowering the victim to the ground where the prone-pressure method may be applied, should it prove necessary.

The results obtained in the field with the pole-top method were excellent, and in 1939 E. W. Oesterreich[3] reported 14 successful resuscitations out of 16 applications. This is an exceptionally fine record when compared with the reports of cases where artificial respiration was not started until the victims had been lowered to the ground.

At the request of the Duquesne Light Company a comprehensive study of the pole-top method was started in the fall of 1939 at The Johns Hopkins University. This is a joint investigation in which its schools of engineering, hygiene, and medicine are co-operating.

This paper presents a report of the first stage of the investigation and deals only with a comparison of the relative amounts of air moved by the standard Schafer prone-pressure method, the modified Schafer method, and the pole-top method.

Paper 40-150, recommended by the AIEE committee on safety, and presented at the AIEE Middle Eastern District meeting, Cincinnati, Ohio, October 9–11, 1940. Manuscript submitted August 7, 1940; made available for preprinting September 13, 1940.

W. B. KOUWENHOVEN is professor of electrical engineering and dean of the school of engineering, D. R. HOOKER is in the school of hygiene, and O. R. LANGWORTHY is in the school of medicine, Johns Hopkins University, Baltimore, Md.

The authors wish to take this opportunity of thanking the Duquesne Light Company of Pittsburgh for funds for carrying on this research and the Consolidated Gas Electric Light and Power Company of Baltimore for furnishing equipment.

1. For all numbered references, see list at end of paper.

Standard Schafer Method

The prone-pressure method of resuscitation was developed by E. A. Schafer[4] in 1907 and has been used widely. In applying this method the subject is placed on his abdomen, with one arm extended and the other bent at the elbow to support the face. The operator kneels, straddling one or both of the subject's thighs, and places his hands on the small of the back. With the arms held straight, the operator swings slowly forward and brings his weight to bear upon the patient. Then the operator swings back quickly so as to remove the pressure entirely. The hands are, however, kept in position on the subject's back. The operation is repeated 12 to 15 times a minute.

Modified Schafer Method

In the modified Schafer method of artificial respiration as employed in this investigation, the "snap-off"[5] method of removing the hands from the subject's back was used. The procedure is similar in every way to that described under the standard prone-pressure method except that the operator releases the pressure suddenly by rolling the palms of his hands outward and thus causing them to slip off the subject's back to the ground.

Pole-Top Method

At the present time the recommended procedure in the pole-top method[3] is as follows:

"1. The first man to reach the victim clears the body from electrical contact permitting the body to hang from the safety strap alongside the pole if possible.

"2. The rescuer then takes a position below the victim on the pole and after placing his safety strap around the pole, proceeds to work his way up with one leg of the victim on either side of his safety strap, and with the body of the victim between himself and the pole. When the safety strap is as high on the pole as can be reached, the weight of the victim's body is taken in a straddle position on the safety strap of the operator.

"3. The mouth of the victim is cleared of foreign substances, the tongue is pulled out and the head pushed forward toward the pole.

"4. The operator then encircles the waist of the victim (under arms) placing both hands, one from each side, on the abdomen of the victim, thumbs below the lower ribs and fingers touching.

Figure 1. Pole-top method of artificial respiration

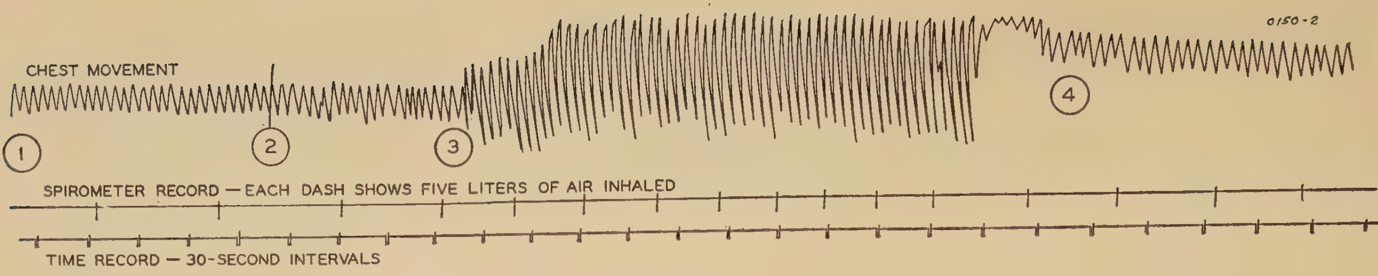


Figure 2. Record of Schafer prone-pressure test

(1) First control. (2) Second control. Operator straddling subject's thigh. (3) Artificial respiration. Note increased chest movement. (4) Final control

"5. The operator applies a constricting action with his arms and hands, obtaining a compression force in an upward direction on the upper abdominal region. At the finish of the stroke the hands should be cupped with the fingers depressing the abdomen under the breast bone. The pressure is then released and periodically reapplied at a frequency of 12–15 per minute until the victim regains consciousness or the resuscitation is to be discontinued."

Subjects

In carrying out this investigation volunteers were chosen from among the students and the staffs of the University. The 15 men tested ranged in age from 20 to 60 years and in weight from 125 to 211 pounds. Each subject is designated by a roman numeral.

All three methods of artificial respiration were applied to each subject. Repeat readings were also made on each man. The time interval that elapsed between successive observations of the same individual varied from five days to one or more weeks.

The results reported in this paper were obtained from men who possessed the ability to relax completely and to place themselves entirely in the hands of the operator. No drugs or anaesthetics were used in the work. Every effort was made to assure the subjects and to convince them by preliminary experiments and trials that there was nothing to fear and that all that was necessary on their part was passiveness. The apparatus was so arranged that they were not cognizant of the results obtained.

Apparatus

The subject breathed through a gas mask connected with a spirometer or gas meter which measured the amount of air inhaled. Each revolution of the spirometer corresponded to five liters of air. The amplitude of movement of the chest and the rate of respiration were recorded on a smoked drum by the change or pressure set up in a pneumograph strapped around the subject's chest. Each revolution of the spirometer and a time mark at 30-second intervals were recorded simultaneously with the record of the respirations. The drum was driven by a clockwork mechanism.

Experimental Procedure

In general, the experimental procedure employed with the Schafer methods was also used in the study of the pole-top method.

In the prone-pressure tests the subject lay face down on a thin mattress which was placed on the floor. With the gas mask on and the pneumograph in place the subject rested for at least ten minutes or until his breathing was regular and normal. The smoked drum was then started and a normal record of the man's breathing taken. Then the operator took his position straddling the subject's thigh. A second or control record of the respiration was taken after a short interval in order to determine if the operator had disturbed the normal rate and amplitude of the subject's breathing. If the two records were similar, then the operator proceeded to apply the designated method of artificial respiration. A complete record of the man's respirations and of the amount of air moved was taken during the period of artificial respiration, which was never continued for more than five minutes so as not to tire the subject.[6] Following the application of artificial respiration, a third control record was taken.

A section of a standard pole approximately ten feet in length was mounted in the laboratory. This was used in the pole-top method studies. The subject was seated on a safety belt which passed around the pole. The ends of the belt were held by a special pipe support in a position which simulated an operator holding the subject. This support was developed so as to relieve the operator of the work of supporting the subject's weight during the period of relaxation and rest.

The subject seated himself on this belt, and with the gas mask and pneumograph in place, rested until his breathing became regular and normal. This usually required about ten minutes. A short record of the subject's breathing was taken, then the operator climbed the pole and took the weight of the subject on his own safety belt. The pipe support was moved out of the way. Several minutes were then allowed to pass and a second or control record of the subject's breathing was taken when respiration had again become uniform and normal. The operator then applied the pole-top method of resuscitation for from three to five minutes. A continuous record was taken on the smoked drum during this period. This

Table I. Records of Four Tests on Subject I, Pole-Top Method of Artificial Respiration

Date of Test (1940)	Operator Holding Relaxed Subject: 10 Liters of Air: Time to Move: Min.	Sec.	No. of Resp.	Rate Resp. Per Min.	C.C. Air Per Resp.	Subject Receiving Artificial Respiration: 10 Liters of Air: Time to Move: Min.	Sec.	No. of Resp.	Rate Resp Per Min.	C.C. Air Per Resp.
2/1	1	20	19	14.6	526	1	00	11	11.0	909
2/6	1	20	19	14.6	526	0	55	13	14.1	769
2/16	1	25	21	14.8	476	1	5	9	8.3	1111
3/15	1	35	21	13.3	476	1	15	12	9.6	833
Av.	1	25		14.3	501	1	4		10.8	906

record was followed by a third control record while the operator still supported the subject. The operator then climbed down and the subject was again supported by the safety belt attached to the pipe support. In this position a final control record of normal breathing was taken.

A photograph of a subject on the pole with the operator in position and about to apply artificial respiration is shown in figure 1.

One of the records taken on the smoked drum is shown in figure 2. The record consists of three parts. The upper saw-toothed line is a record of the movement of the subject's chest. The increased movement during the period of artificial respiration may be seen clearly. Each dash in the middle line indicates that the subject has inhaled five liters of air. The increase in the amount of air moved during the application of artificial respiration is shown by the closer spacing of the vertical dashes. Each break in the bottom line records the passage of 30 seconds of time.

Three different individuals served as operators who gave artificial respiration during this investigation. Most of the work, however, fell to the lot of one experienced operator. The results obtained by different operators on the same subjects check remarkably well and give evidence of the uniformity of the work and of the passiveness of the subjects. Not only was the subject ignorant of the results obtained, but the operator was also in such a position as to prevent his seeing the record during the period of the application of artificial respiration.

Results

The results are given in tabular form. A small amount of resistance was introduced by the subject's breathing through the mask and the spirometer. Measurements of the variations in pressure in the mask were made with a water manometer. They were found to amount to less than one inch of water pressure. No corrections were made for these variations nor were corrections made for changes in barometric pressure or temperature of ambient air.

Variations Between Tests of Same Individual

As stated, two or more records were made on each individual by each of the three methods of artificial respiration studied. In table I the results for four separate records on subject I using the pole-top method are given. Two different operators were used on this subject. The data illustrate the differences found in repeated tests on the same individual.

Rates of Respiration

In table II are given the rates of respiration with the subject relaxed and lying prone in both the standard and modified Schafer methods and with the subject relaxed and sitting on the operator's belt in the pole-top method. In addition, the rate of breathing for all three methods of artificial respiration is also given. The age and weight of each subject is included in table II.

Lying prone in a relaxed posture the average rate of respiration was practically identical for the standard and modified Schafer methods. With the subjects sitting on the operator's belt the normal rate of respiration is somewhat higher as would be expected. The average rate of application of artificial respiration was substantially the same, namely, 11 times per minute, in both of the prone-pressure methods, and at a slightly less tempo, about 10 per minute, in the pole-top method.

Air Moved Per Respiration

Table III gives the cubic centimeters of air moved per inspiration for the subjects relaxed in the prone and sitting positions and for all three methods of artificial respiration studied. The air moved per respiration was naturally found to be the same for the two tests where the subjects were lying on the mattress. In the sitting position, it was slightly higher than for the prone position.

The artificial respiration results are given in the last three columns of table III. In the standard Schafer method the average was 868±51 cubic centimeters, and in the modified Schafer method 1,028 ±57 cubic centimeters. The pole-top method gave an average 1,363±85 cubic centimeters per inhalation. The

Table II. Rate of Respiration Per Minute During Control and Artificial Respiration Periods

			Control			Artificial Respiration		
Subject	Age	Weight (Lbs)	Std. Sch. Lying Prone	Mod. Sch. Lying Prone	Pole-Top Sitting on Belt	Std. Schafer	Mod. Schafer	Pole-Top Method
I	60	155	13.2	10.8	14.3	9.1	11.5	10.8
II	54	175	15.3	14.3	16.8	12.0	11.0	10.8
III	42	134	14.5	11.1	16.9	13.7	9.6	7.0
IV	36	140	10.4	10.6	12.0	8.9	9.2	10.3
V	34	188	15.7	17.1	14.7	8.5	10.6	8.3
VI	24	125	13.7	13.6	14.3	8.6	11.4	7.5
VII	27	145	16.6	12.4	15.6	10.5	8.7	8.2
VIII	31	160	12.8	12.8	19.2	15.3	11.7	10.4
IX	27	211	12.0	12.0	12.0	12.3	12.0	10.9
X	20	148	9.0	9.0	8.1	8.1	6.6	8.1
XI	20	193	12.4	12.4	18.0	13.3	12.2	13.8
XII	49	130	11.2	11.2	9.4	5.3	6.5	4.7
XIII	28	140	15.3	15.3	15.1	14.5	13.3	10.9
XIV	38	160	12.8	12.8	13.7	11.6	10.1	12.9
XV	21	140	17.8	22.2	23.0	14.9	18.1	20.1
Av.			13.5	13.2	14.9	11.1	10.8	10.3

Table III. Cubic Centimeters of Air Moved Per Respiration

	Control Period Subject Relaxed			Subject Receiving Artificial Respiration		
	Lying Prone		Sitting on Belt			
Subject	Std. Sch.	Mod. Sch.	Pole-Top	Std. Sch.	Mod. Sch.	Pole-Top
I	463	410	501	635	839	906
II	528	505	509	729	972	1,485
III	576	576	526	611	1,340	1,340
IV	646	572	607	955	1,010	1,111
V	445	495	501	913	955	1,270
VI	403	467	451	769	646	1,429
VII	417	635	557	1,389	1,625	2,500
VIII	635	635	396	607	749	801
IX	667	667	714	625	714	1,000
X	662	662	742	1,111	1,270	1,667
XI	667	667	574	679	1,056	1,056
XII	555	555	742	1,500	1,715	2,250
XIII	488	466	500	572	628	837
XIV	487	487	530	850	932	1,459
XV	528	400	526	1,080	972	1,340
Av.	544	546	558	868	1,028	1,363

Behavior of Point Gaps at 60 Cycles

JEAN V. LEBACQZ
ASSOCIATE AIEE

VALUES of arc-over voltages for point gaps in air have often been considered rather inconsistent and difficult to reproduce with reasonable accuracy. Accordingly, a study was made to determine, first, if certain types of electrodes might give more consistent results than others and, if so, under what conditions, and, second, whether or not it would be possible to derive a formula which would take into account disturbing factors such as humidity. The results of this study are summarized in this paper, which, the author hopes, may be a small contribution toward a better understanding of arc-over phenomena.

Equipment

The gaps tested were set up vertically in the center of a specially built cylindrical chamber, 12 feet high and 12 feet in diameter, both the floor and ceiling of the chamber being made conducting in order to minimize the disturbances from surrounding objects on the field around the gap. One electrode was grounded, the other one being connected to the high-voltage side of a 350-kv 350-kva testing transformer. The air humidity in the chamber was controlled by the introduction of water vapor.

The electrodes studied are classified as follows:

Electrode Number	Description
1	$^9/_{16}$-inch round rod ended by a 15-degree cone
2	$^9/_{16}$-inch round rod ended by a section perpendicular to its axis
3	$^9/_{16}$-inch round rod ended by a 90-degree cone
4	$^9/_{16}$-inch round rod ended by a 120-degree cone
5	$^1/_2$-inch square rod ended by a section perpendicular to its axis
6	$^9/_{16}$-inch round rod ended by a hemisphere
7	Loud-tone phonograph needles

All the electrodes except the phonograph needles were made of brass.

To avoid erratic results due to oxidation and burning of the electrodes, an ultrahigh-speed circuit breaker was built and placed in the circuit. The arc current was actually interrupted by this breaker the first time it went through zero after the arc started—that is, in one quarter of a cycle or approximately $^4/_{1,000}$ second. This eliminated almost completely the burning of the points; and the pitting of the electrodes after more than 30 spark-overs with this breaker in the circuit was much less noticeable than that corresponding to one arc-over interrupted by a five- or six-cycle circuit breaker. It is the writer's belief that, without the use of this circuit breaker, the results herein described could not have been obtained. With a conventional type of breaker, it would have been necessary to change the points after each arc-over, a very lengthy and tedious task considering that, in order to derive the conclusions found, about 6,500 values of arc-over have been observed. A brief description of this high-speed breaker is given in appendix.

Paper 40-131, recommended by the AIEE committee on instruments and measurements, and presented at the AIEE Pacific Coast convention, Los Angeles, Calif., August 27–30, 1940. Manuscript submitted May 13, 1940; made available for preprinting July 24, 1940.

JEAN V. LEBACQZ is instructor in electrical engineering, University of California, Berkeley.

The author is presenting in this paper a summary of the work he did at the H. J. Ryan high-voltage laboratory of Stanford University for his doctoral dissertation while he was a fellowship student of the Belgian-American Educational Foundation. He wishes to take this opportunity to express his appreciation to both Stanford University and the Belgian-American Educational Foundation for the facilities extended to him, and his sincere gratitude to Doctor J. S. Carroll for the aid and helpful suggestions given him.

---

plus-minus values given above are the probable error in the arithmetical mean and were calculated by the method of least squares.[7] A study of table III shows clearly that for every individual tested the amount of air moved per respiration in the pole-top method was equal or greater than that for either of the other two methods studied. The rate of respiration is, however, slightly less in the pole-top method than in the others. (See table II.)

It is also clear from the data that all three methods produce adequate ventilation of the lungs. In many of the subjects at the termination of artificial respiration there was a diminished concentration of carbon dioxide and an increased concentration of oxygen in the blood. The respiratory centers in the brain were not stimulated to activity and a brief period of apnea resulted. Soon normal breathing was resumed. This is clearly shown in the record in figure 2 where there is a brief pause in the chest movement following artificial respiration.

While in general, the modified Schafer method, where the hands are "snapped-off" the subject's back, moves more air than the standard prone-pressure method, it would, if continued for any length of time, tend to remove the skin from the subject's back.

Time to Move Ten Liters of Air

A very interesting method of studying the results is to compare the time required for the subject to breathe ten liters of air. When this was done, the average times are found to be as follows:

	Minutes	Seconds
Control period—lying prone	1	22
Control period—sitting on belt	1	12
Standard Schafer method	1	2
Modified Schafer method	0	54
Pole-top method	0	43

The above comparison shows clearly that all three methods of artificial respiration studied are efficient and that the actual volume of air moved by their use in a given time is comparable to the amount that the subject would breathe under normal conditions.

Conclusion

It is evident that the ventilation of the lungs obtained by the pole-top method is adequate and that the subject receives sufficient oxygen to satisfy his needs.

Bibliography

1. Using Vital Moments in Saving a Life. NELA *Bulletin*, April 1932, page 228.

2. Remarks on Pole-Top Resuscitation, C. K. Drinker. National Safety Congress and Exposition, October 1939.

3. The Pole-Top Method of Resuscitating Linemen After Electric Shock, E. W. Oesterreich. Pennsylvania Electric Association, March 1, 1939.

4. Harvey Society Lectures, E. A. Schafer, page 223, 1907–08.

5. First Aid Text Book, American Red Cross, 1937 edition, page 113.

6. Adventures in Respiration (a book), Y. Henderson, 1938 edition, page 273.

7. Method of Least Squares (a book), M. Merriman. 1911 edition, page 70.

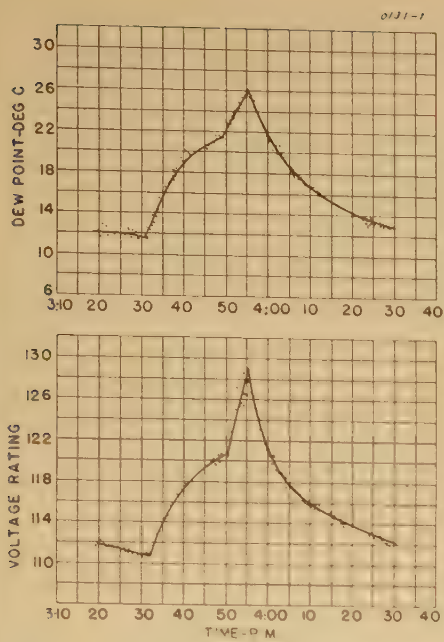


Figure 1. Variation of humidity and corresponding variation of arc-over voltage as a function of time

Gap number 3; spacing 12 inches; barometric pressure 29.9 inches of mercury

Apparatus

The voltage was measured directly from the voltmeter coil of the testing transformer. It must be noted that the purpose of this study was not to calibrate the point gaps, but to determine the relative effect of various factors on their arc-over voltages. For relative values only, the accuracy of these measurements may be considered as being better than 0.5 per cent.

The measurement of humidity required elaborate equipment. It was necessary to know, at all times, the value of absolute humidity inside the test chamber. To do this, a semiautomatic dew-point hygrometer was built according to the following principle:

Light emitted from a constant source was reflected onto a photoelectric cell by a highly polished nickel surface. If dew forms on the nickel surface, the amount of light reflected, and hence the current in the photoelectric cell, decreases. If the nickel surface is soldered on a wall of a small copper vessel, its temperature will be controllable by changing the proportions of a mixture of ice cold and hot water flowing through the vessel. This change can be achieved by the variation of current in the photoelectric cell, setting into action a suitable system of relays, motor, and valve in the hot-water circuit, to increase the temperature of the mixture as soon as dew is formed and to decrease it when dew has disappeared.

The temperature of the polished surface does not, however, respond immediately to the change of current in the photoelectric cell; to prevent any error that might occur from overshooting, a special device has been arranged to give exactly the time at which the dew forms or disappears on the polished surface. The temperature is measured by thermocouple; the polished nickel, being soldered on a sheet of copper, is used as the warm junction, the cold junction being immersed in melting ice. The resulting electromotive force is applied directly to a galvanometer, and readings are taken both when the dew forms and when it disappears, the average being taken as the true dew point. Tests made to determine the accuracy of this semiautomatic dew-point hygrometer showed that, under the most adverse conditions, the error in the dew-point temperature does not exceed 0.2 degree centigrade.

Tests and Procedure

The behavior of the following gaps has been studied:

Gap Number	Electrode Number High Voltage	Electrode Number Ground
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	5	1

Spacings ranging from 6 to 30 inches were studied, except with gap number 7, for which the maximum spacing studied was 12 inches.

All the tests were made by varying the absolute humidity from approximately 10 to 25 millimeters of mercury. The air density was practically constant during the tests. It was not possible, however, to prevent a slight increase in temperature when the humidity was increased artificially by the introduction of water vapor in the test chamber. The resulting change in air density never amounted to more than two per cent.

Since the humidity inside the test chamber was varied continuously, the dew point was recorded as a function of time, while the value of arc-over voltage was observed every 30 seconds. The results are plotted as a function of time, and the average curves drawn (sample curves are given in figure 1). From these curves, the relation between the humidity and the voltage may be easily deduced. They also make it easy to determine under what conditions the readings are erratic, and also if they must be considered as low or high compared to the average.

Results

The results obtained will now be discussed by considering: first, the influence of the shape of the electrodes on the arc-over voltage; second, the combined influence of both the shape of the electrodes and the absolute humidity on the behavior of the gap; third, the effect of humidity for each type of electrode; and, finally, some of the other factors affecting the arc-over voltage.

1. Influence of the Shape of the Electrodes

Table I gives, in kilovolts effective, the arc-over voltages observed at a humidity of 15 millimeters of mercury for the different types of electrodes studied.

It is seen that the arc-over voltage for gap number 2 is 60 per cent greater at 18 inches and 35 per cent greater at 24 inches than that of any other gap. The arc-over could not be observed at 30 inches, but it is more than 20 per cent greater than that of the other gaps (over 360 kv). With that exception, all values observed at 18, 24, and 30 inches check within less than five per cent. Since no correction has been made for air density—the influence of which may amount to one or two per cent—and since, at the same air density, variations of a few per cent may occur for the same type of gap, it may be

Table I

Spacings (Inches) Gap Number	6	12	18	24	30
1	60.1	117.5	173	236.8	298.7
2	117.5	205	283	320	
3	61.5	119.2	181.5	239.5	302.5
4	66.3	119	177.5	244.3	297
5	85	136	179.6	235.8	296.5
6	72	120	174.2	237	298
7	61.2	116.3			
8	63.8	115	173.5	229.5	293.8

stated that, at these spacings, all the gaps studied in these tests give approximately the same arc-over voltage, except gap number 2.

The results at 12 inches spacing check within four per cent for all types of electrodes except two, and may thus also be said to be identical. The two exceptions are gap number 2, with an arc-over voltage 70 per cent higher, and gap number 5, which gives results approximately 15 per cent higher, than the others.

The arc-over voltage at six inches spacing is much more influenced by the shape of the electrodes; gaps numbers 1, 3, and 7 give the same value, and as the result for gap number 8 is only 4 per cent higher it may thus still be considered the same. The other results are higher; for gap number 4 by 12 per cent; for gap number 6 by 20 per cent; for gap number 5 by 40 per cent; and for gap number 2 by 95 per cent.

These results show that, as was expected, the smaller the spacing, the greater the influence of the shape of the electrodes.

2. Erratic Nature of Point Gaps

Gap number 2 will not be considered in the following discussion, because it gives erratic results at all spacings studied, and its arc-over voltage is always much higher than that of gaps formed by the other electrodes. The results obtained for the other gaps are shown in figure 2, *a* to *e*, and explained hereafter.

At six inches spacing, gap number 1 gives consistent results when the electrodes are clean. When they are burned, however, the readings are erratic and appreciably higher than those of clean points. The same effect has been observed for the phonograph needles, where a slight burning of the tip tends to make the results erratic and to increase the average arc-over value; however, at high humidity, the readings stay consistent even with the points slightly burned. Gap number 3, when clean, gives consistent results, while gaps 4, 5, and 6 are erratic; their arc-over voltage is greater than that of the gaps giving consistent results. The results obtained with gap number 8 are fairly consistent.

It may thus be stated that, at six inches spacing, the results will be consistent as long as the electrodes end in a single well-defined point, and erratic under the other conditions.

The results at 12 inches spacing are very similar to those obtained at 6 inches, except that the tendency for erratic readings with a none-too-well-defined point is less marked; for instance, gap number 4 gives consistent results at this spacing and erratic ones at 6 inches. It may also be stated that the results will be consistent as long as the electrodes end in a single well-defined point.

At 18 inches spacing, the results are very consistent for all gaps under all the conditions studied.

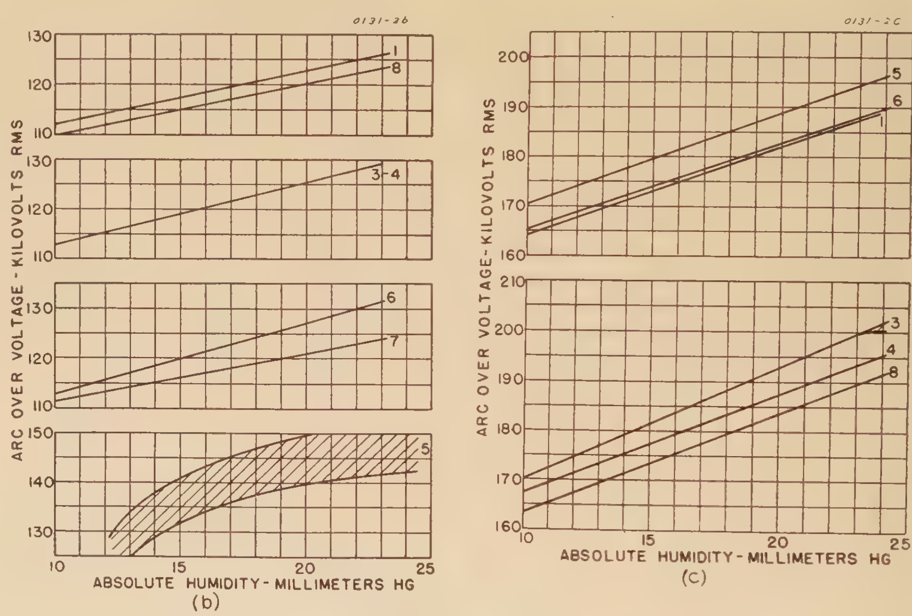


Figure 2, a to e. Variation of the arc-over voltage as a function of absolute humidity for the gaps studied at the following spacings:

(*a*)— 6 inches
(*b*)—12 inches
(*c*)—18 inches
(*d*)—24 inches
(*e*)—30 inches

The number on each curve corresponds to the gap number as given in this paper

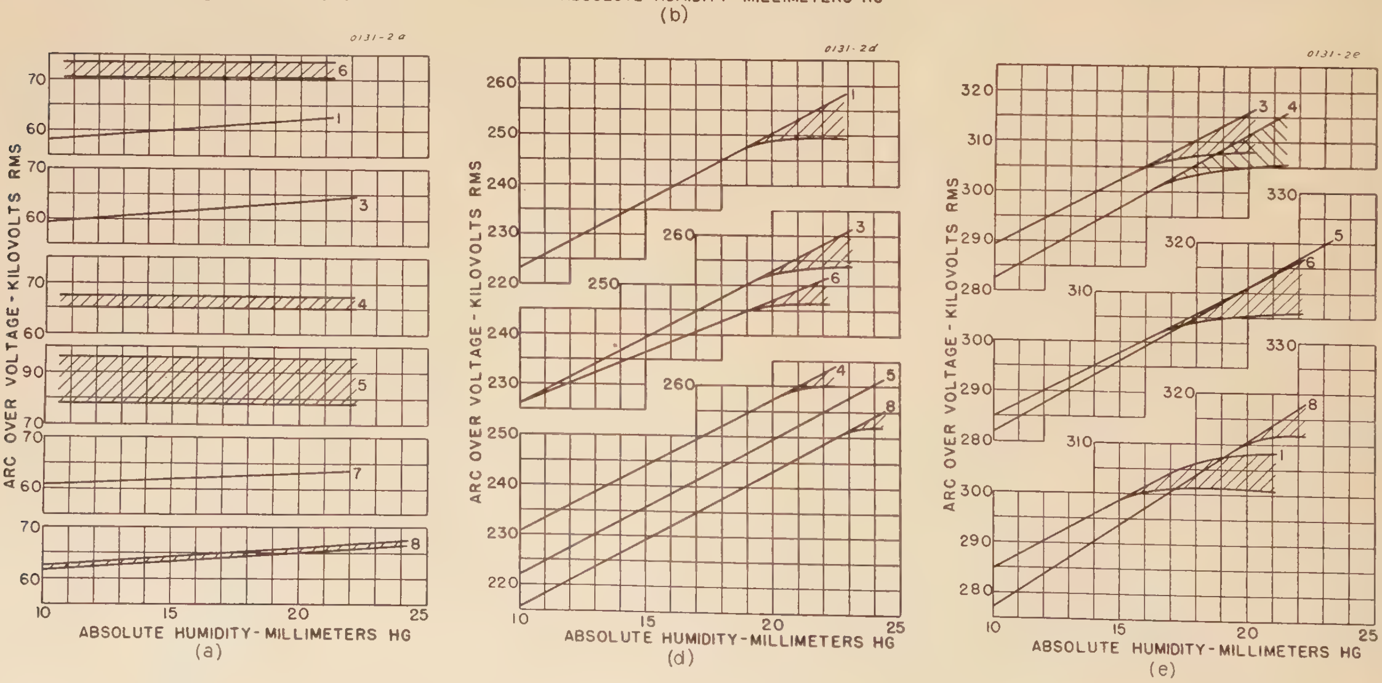


Table II. Values of Arc-Over Voltage in RMS Kilovolts as a Function of Spacing and Absolute Humidity for the Gaps Studied

Gap Number	Humidity (Mm Hg)	Spacing (Inches) 6	12	18	24	30
1	10	58.1	112	164	223.3	284.7
	15	60.1	117.5	173	236.8	298.7
	20	62.1	122.8	182	250.2	(305.6)
2	10	116.6	200.5	277.5		
	15	117.5	205	283		
	20	118.6	(208)	288.5		
3	10	59.4	113	170.2	226	289.3
	15	61.5	119.2	181.5	239.5	302.5
	20	63.6	125.5	192.9	253	315.8
4	10	(66.3)	112.7	167.5	231.2	282.5
	15	(66.3)	119	177.5	244.3	297
	20	(66.3)	125.5	187.5	257.5	311.5
5	10	(85)	?	170.5	222	281.7
	15	(85)	(136)	179.6	235.8	296.5
	20	(85)	(144.5)	189	249.5	311.2
6	10	(72)	112.8	165.4	226	285
	15	(72)	120	174.2	237	298
	20	(72)	127	183	247.2	311
7	10	60 9*	111.4			
	15	62.1*	116 3			
	20	63.2*	121			
8	10	62	109.8	163.5	215.6	277.2
	15	63.8	115	173.5	229.5	293.8
	20	65.5	120.2	183.5	243.2	310.5

Note: Values in brackets have not been used for computing the relative influence of humidity.

* These values correspond to a spacing of $6^{3}/_{32}$ inches.

At 24 inches spacing, gap number 5 is the only one to give consistent results for all the conditions studied. With all the other electrodes, the results are consistent below a certain value of humidity, which will be referred to as "critical humidity". Above that value, they are always very erratic; the maximum readings fall on the extrapolated curve of voltage-humidity, but the average is notably decreased. Besides, it seems that, if the humidity is increased much farther, the voltage stays practically constant. The critical value of humidity appears to be approximately 20 millimeters of mercury for gaps numbers 1, 3, 4, and 6, and 23 millimeters of mercury for gap number 8.

The results at 30 inches spacing are entirely similar to those obtained at 24 inches; gap number 5 gives consistent results under all the conditions tested, while the others show a critical humidity, beyond which the average is decreased below the values expected from extrapolation. The critical value of humidity is approximately 17 millimeters of mercury for gaps numbers 1, 3, 4, and 6, and 20 millimeters of mercury for gap number 8.

The conclusion, therefore, is that, in order to obtain consistent results with the rod diameter used and at spacings between 6 and 18 inches, clean electrodes ending in a single well-defined point must be used. At spacings between 18 and 30 inches, however, a type of electrode offering several sharp points—such as a square rod ended by a plane section—should be used to obtain consistent results under all humidity conditions. Finally, a composite gap such as gap number 8 shows characteristics similar to those of gap number 1 at small spacings, while at large spacings, its behavior approaches that of gap number 5.

3. Influence of Humidity

For all the electrodes studied, the arc-over voltage increases linearly with the absolute humidity. There are, however, two exceptions. At six inches spacing, the arc-over voltage of the electrodes which give very erratic results does not seem to be influenced by humidity. At large spacings, when the humidity is greater than its critical value, the proportionality law holds true only if the maximum instead of the average readings are considered; and, for still higher values of humidity, the arc-over voltage seems to become independent of humidity.

Since the function of arc-over voltage versus humidity is linear, it was easy for comparison to compute the value of "relative influence of humidity". The author has called relative influence of humidity the percentage of increase in arc-over voltage corresponding to an increase of one millimeter of mercury of water-vapor pressure. It is thus given by:

$$I_h = 10 \frac{V_{20} - V_{10}}{V_{15}} \text{ in per cent}$$

where V_{10}, V_{15}, and V_{20} are the arc-over voltages corresponding respectively to values of absolute humidity of 10, 15, and 20 millimeters of mercury. The values of I_h, obtained from tables II and III (see appendix), are plotted on figure 3, *a* and *b*.

It is seen immediately that the influence of humidity is far from being constant at all spacings. It attains a maximum of approximately 1.2 per cent per millimeter of mercury for spacings between 18 and 24 inches. On the other hand, the values observed may be considered as practically independent of the type of electrodes—with the exception of those observed with gap number 2.

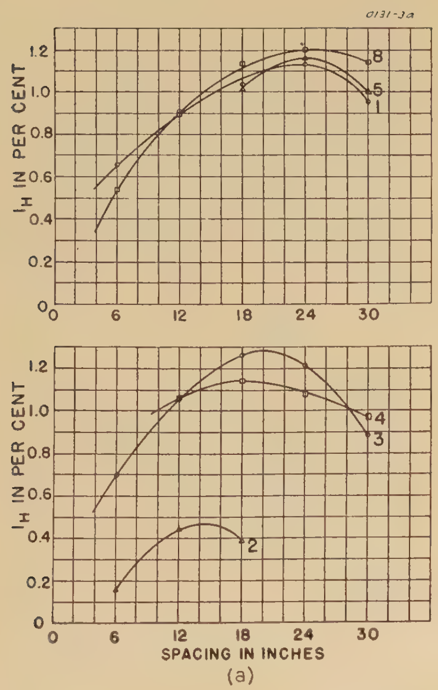
4. Other Factors Affecting the Arc-Over Voltage

Some observations made showed—as had already been observed—that the point gaps arc-over voltage increases with air density. However, no systematic study of that factor was made during these tests.

Some other factors as yet unknown have a decided influence on the point gaps arc-over voltages: differences as high as three per cent were observed from one day to another—sometimes even on the same day when the air of the test chamber had been disturbed—even if the temperature, barometric pressure, and humidity were exactly the same. It is supposed that these factors are either vapors or impurities such as dust parti-

Table III. Values of Relative Influence of Humidity I_h in Per Cent as a Function of Spacing for the Gaps Studied

Gap Number	Spacing (Inches) 6	12	18	24	30
1	0.67	0.92	1.04	1.14	0.94
2	0.17	0.44	0.39		
3	0.68	1.05	1.25	1.12	0.88
4		1.07	1.13	1.08	0.98
5			1.03	1.17	1.00
6		1.18	1.01	0.91	0.87
7	0.37	0.82			
8	0.55	0.90	1.15	1.20	1.13



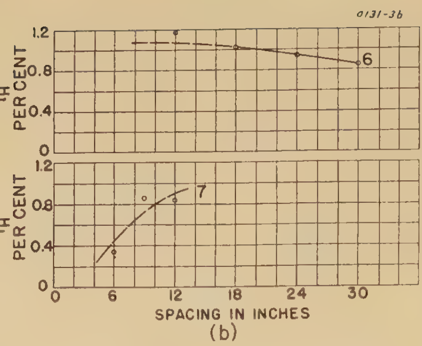


Figure 3, a and b. Relative influence of humidity I_h as a function of spacing for the gaps studied

The number on each curve corresponds to the gap number as given in this paper

cles in the air. This assumption is based on two observations made with gap number 1, at six inches spacing. The introduction of small quantities of ether vapor in the test chamber increased the arc-over voltage by approximately 17 per cent. A noticeable increase in voltage was also observed after introduction in the test chamber of vapors from moist wood. Lack of time unfortunately prevented any systematic research along these lines.

Conclusions

The results obtained from approximately 6,500 point gaps arc-overs under varying conditions may be summarized as follows:

1. The voltage at all spacings up to 30 inches increases linearly with an increase in absolute humidity.

2. The percentage of increase in voltage per millimeter of mercury increase in water vapor pressure is not constant at all spacings:

(*a*). It attains a maximum value of 1.2 per cent per millimeter of mercury for spacings between 18 and 24 inches;

(*b*). It is practically the same for all the electrodes studied in these tests.

3. At spacings of 18 inches or more, the arc-over voltage is practically the same for all the electrodes studied, provided they are ended by a finite number of points.

4. The readings are erratic at small spacings if the electrodes do not end in a single well-defined point or if that point becomes burned, thus offering a rough surface. The average is then greater than that obtained for a clean point.

5. Except for the electrodes number 5 ($^1/_2$-inch square rod ended by a section perpendicular to its axis) the readings are erratic at large spacings for high values of humidity. The average is then smaller than would be expected by extrapolation of the results obtained at lower humidity.

6. Under all the other conditions studied, the results were very consistent.

7. It is possible, by using two different types of electrodes, to obtain a gap partaking of the advantages of each electrode of which it is made.

8. Impurities or other vapors in the air affect the arc-over voltage.

Appendix

High-Speed Circuit Breaker

The ultrahigh-speed circuit breaker used in this experiment consisted primarily of a vertical plunger-type electromagnet, bearing three separate windings. The plunger had a displacement of approximately three-eighths inch, and acted on two sets of moving contacts of the breaker. It was rigidly connected to a pair of current-carrying contacts, and, during the last one-fourth inch of its travel, it opened a pair of arcing contacts. This ensured a total gap of one-half inch, quite sufficient to break a 2,000-volt circuit under oil.

The main winding carried the total primary current of the high-voltage transformer; the second winding created a flux exactly opposed to that produced by the exciting current of the transformer flowing in the first winding; and the third winding merely acted as a hold-open device.

The main winding was so designed that the pull on the plunger averaged about 80 times the weight of the plunger during the first one-fourth cycle of the arc-over current. At the end of this one-fourth cycle, the current went through zero, since it starts on the crest of the voltage wave and is practically in phase with the voltage. At the same time, the current carrying contacts had separated about $^3/_{16}$ inch, and the arcing contacts were beginning to move at such a velocity that the insulation between them and the stationary contacts was building up faster than the recovery voltage, thus preventing the arc from being established.

The purpose of the second winding was to prevent any pull on the plunger that might be caused by the exciting current, the value of which was approximately $^1/_{20}$ of the arc-over current. Besides, it created the only flux keeping the contacts open between the interruption of the arc-over current and the establishment of the current in the third winding.

The third winding was necessary because the contacts were not designed to close the circuit and had to be kept open until the generator voltage was brought down to zero, thus preventing any rush of exciting current while the contacts were closing. A suitable system of relays was set up so that after the breaker had opened the circuit, current started flowing in the third winding, and by manual operation of a single switch, the generator voltage was brought down to zero, the breaker closed, and the transformer voltage built up to about 90 per cent of the expected arc-over value.

The operation of this breaker proved to be very satisfactory, since practically no arcing was visible, even when interrupting currents of 300 amperes rms at 2,000 volts.

Bibliography

1. Influence of Humidity on Surge Flashover, **F. D. Fielder.** *Elec. J.*, July 1932.

2. Normal-Frequency Arc-Over Values of Insulators as Affected by Size and Humidity, **H. A. Frey** and **K. A. Hawley.** AIEE Transactions, September 1932.

3. Insulator Sparkover, **W. L. Lloyd, Jr.** AIEE Transactions, September 1932.

4. Flashover Voltages of Insulators and Gaps, Committee Report. Electrical Engineering (AIEE Transactions), volume 53, 1934, page 882.

5. Impulse and 60-Cycle Strength of Air, **P. L. Bellaschi** and **W. L. Teague.** Electrical Engineering (AIEE Transactions), volume 53, 1934, page 1638.

The Effect of Overexciting Transformers on System Voltage Wave Shapes and Power Factor

J. W. BUTLER
MEMBER AIEE

E. B. POPE
ASSOCIATE AIEE

IT is well known that the voltage and current wave shapes of transmission and distribution circuits are distorted more or less from a true fundamental-frequency sinusoid. Several years ago extensive tests were conducted, measuring the wave shapes for different types and voltages of circuits.[1] There were however no definite conclusions drawn concerning the origin or improvement of these wave distortions.

Measurements by the authors of harmonics on various systems in the country, as well as those measurements referred to, show in general that the harmonic voltages increase in magnitude as the measurements are made farther and farther from the generating stations. This indicates that probably transformer exciting currents have more effect on system wave shapes than is usually given credit.

The nontriple odd-harmonic frequency components of exciting currents of all the transformers in a system are supplied by generators, load circuits, or system capacitances. The ohmic values of the load and capacitive circuit impedances are usually many times those of the circuits which include the generating points or similar large rotating machines. Hence, practically all of the nontriple-frequency components of exciting current for transformers can be said to be supplied by the generators.

With this thought in mind one can appreciate that transformers in outlying districts may have to draw their exciting current through a great deal of impedance. Current going through impedance naturally produces voltages in accordance with Ohm's law so it can well be expected that under the proper conditions the harmonic content of these exciting currents could have a measurable effect on system wave shapes. Further, it is well known that in general, due to inadequate regulating equipment, and other reasons, certain transformers are overexcited in order to deliver the desired voltages at the load. It is, however, not so well recognized that this overexcitation greatly magnifies these system harmonics and reduces the system power factor. This reduction in power factor results in less boost in voltage than is expected with the final result being *excessive* overexcitation in certain areas, with the attendant decreased power factor, increased losses, and increased harmonic content of the voltage and current waves. It was the desire to determine more or less quantitatively what effect this overexcitation of transformers might have on system wave shape and power factor that prompted this study.

Experience and measurements show in general that the third-harmonic voltages and currents are relatively small. This is because nearly all three-phase transformer banks have one winding connected delta, which permits the triple-frequency currents to circulate thus preventing them from flowing beyond the first delta winding. The only triple-frequency voltage then that gets out on the system is that which represents the impedance drop in the lines to the first delta and the delta windings themselves of the third harmonic currents. Experience shows that the fifth harmonic is generally the largest single harmonic component in the current and voltage waves. It is appreciated that the magnitude of various harmonics varies considerably in any given system, but in general it has been found that the fifth is the largest component. Admittedly, in isolated cases motors or generators generate higher frequencies known as "slot ripples", which may need special attention, but this phase of the subject is not studied.

In order, therefore, to assign definite objectives to the problem, it was decided to study the effect of transformer overexcitation in a sample system on the fifth-harmonic voltage and power factor and determine what practical methods were available for improving these conditions if and when they required it.

General Method of Attack

The hypothetical system represented by figure 1 was chosen for study. Average typical circuit constants and transformer ratings were assumed as listed in table I. This circuit, with each transformer represented by its equivalent with a harmonic generator in its magnetizing branch for supplying harmonic current (refer to figure 2 and appendix) was set up on the a-c network analyzer. With this arrangement, the circuit constants, the magnitude of harmonic current flow for different values of excitation, and the ratio between substation and distribution transformer capacity could be readily varied.

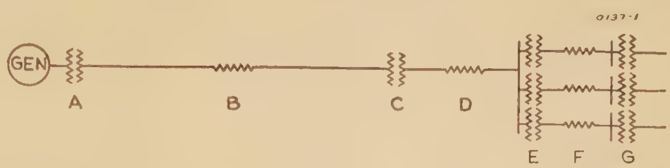


Figure 1. Diagram of the hypothetical system analyzed

Refer to table I for explanation of symbols

With a predetermined excitation on the transformers, the magnitude of the fifth-harmonic current required was made to flow by adjusting the voltage of the harmonic generator in each transformer circuit. With these adjustments made, the fifth-harmonic voltage was then read at any desired point in the system. This procedure was carried out for normal and 110 per cent excitation on all transformers.

This type of test assumes a pure sine wave of fundamental voltage is applied to each transformer, which is not true in the strictest sense of the word since the reactance from the voltage source to each transformer results in small harmonic voltages being applied instead of a pure sine wave. This error is small for the value of voltages encountered hence the effect is neglected.

Conclusions

1. A small negligible value of fifth-harmonic voltage can be expected to appear in transmission and distribution circuits as a

---

Paper 40-137, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE Middle Eastern District meeting, Cincinnati, Ohio, October 9–11, 1940. Manuscript submitted April 12, 1940; made available for preprinting August 9, 1940.

J. W. BUTLER and E. B. POPE are in the central-station department of the General Electric Company, Schenectady, N. Y.

1. For all numbered references, see list at end of paper.

result of the flow of fifth-harmonic components of exciting currents required by normally excited transformers.

2. This fifth-harmonic voltage is more than doubled when the excitation on the majority of the transformers in a system is increased ten per cent.

3. The over-all system power factor can be materially reduced by exciting currents resulting from *excessive* overexcitation of the majority of the transformers.

4. Since the advantages of operating at the present established levels of meter-box voltages cannot be denied, distribution systems utilizing a large proportion of the older designs of distribution transformers requires more careful operation and regulation in order to not exoessively overexcite the transformers.

5. The use of capacitors and reactors in series for the dual pupose of power-factor and wave-form improvement provides a simple, effective, and economically sound method of coping with these two problems presented by the overexcitation of transformers.

6. The replacement of obsolete distribution transformers with up-to-date built-for-the-service equipment would reduce these harmonic voltages, excessive exciting currents and losses, caused by overexcitation. This point should be more closely scrutinized by distribution engineers, particularly in view of the recent advances made in the art of building distribution transformers.[2]

7. The objectionable conditions arising from the overexcitation of transformers should further encourage the movement attempting to standardize circuit and appliance voltages so that further increases in transformer voltages will be unnecessary.

Transformer and Circuit Data of System in Figure 1

The system analyzed and represented by figure 1, does not necessarily represent any particular system in existence but it does represent in substance the equivalent amount of transformers and lines that might be used in transmitting and distributing a given block of power.

The power transformers in the line are assumed to be of 100 per cent capacity while each of the three step-down substation transformers are taken as 50 per cent capacity. Diversity in feeder loads usually requires at least this ratio of capacities. The complete circuit data including ratings and reactances of the various lines and transformers, and the per cent exciting currents used are listed in table I. For purposes of this study, it is assumed that an average normal density of 70 kilolines per square inch is representative for the distribution transformers and a density of 85 kilolines for the power transformers.

In figure 3 are plotted the data of a harmonic analysis of the exciting current of a representative iron that might be used for transformers. Thus, for the different values of excitation studied the per cent harmonic content of the exciting current can be obtained. It should be noted that these data give the per cent harmonic content of the total exciting current. Since it is the *total* amperes of harmonic current flowing that determines the voltage, these percentage values must be co-ordinated with the actual magnitudes, of exciting current. A certain transformer under an overvoltage condition might require 10 per cent total exciting current having 10 per cent fifth harmonic while another could require 4 per cent total current but having 20 per cent fifth. Thus the one having a *less percentage* of fifth may actually have *more amperes* of fifth harmonic.

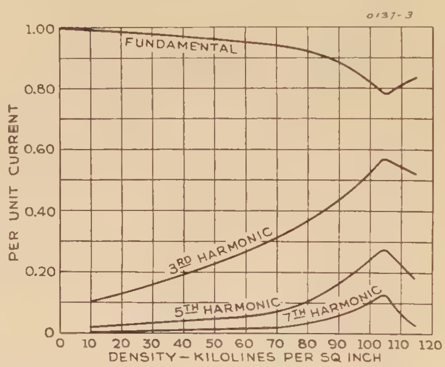


Figure 3. Harmonic analysis of the exciting current of a representative sample of iron that might be used for transformers

Data plotted as per unit of total exciting current against density

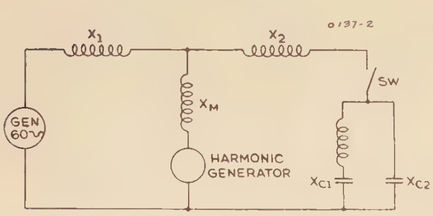


Figure 2. Diagram of equivalent transformer circuit with harmonic generator in the magnetizing branch for supplying the required harmonic currents. The switch connects a series reactor-capacitor combination for improving wave form and power factor—refer appendix

Normal Excitation on All Transformers

This study involved the determination of the fifth-harmonic voltages in the hypothetical system laid out in figure 1 for normal excitation on all transformers. This is indeed somewhat of a hypothetical condition, since never would a system be found that had normal voltage applied to all transformers. However it does have the academic value of showing to what extent normal-excitation exciting currents would generate harmonic voltages in such a system.

The voltages that the prescribed values of harmonic current caused to appear in the test system are shown plotted by the solid lines in figure 4. Curve *A* represents the conditions when the ratio of distribution to substation capacity is unity. Here it is seen that the fifth-harmonic voltage gradually rises from zero at the generator to approximately 0.02 per unit in the distribution area. The solid curves labeled *B* and *C* show the voltages when the distribution-transformer capacity ratio was increased to 2 and 3 respectively. Here it is seen that the harmonic voltage increases slightly for these two conditions. These figures are representative of the lower values of fifth-harmonic voltages measured in actual systems.

1.1 Per Unit Excitation on All Transformers

The next consideration was that of determining the fifth-harmonic voltages when all the system transformers were overexcited ten per cent. Again, the reader is cautioned that this does not necessarily represent a practical case, but it does show, when compared with the results of the previous case how the harmonic voltages can be expected to increase when the transformers are operated above their normal densities.

The exciting currents for this condition of excitation, for the two types of transformers are listed in table I.

Cases *A*, *B*, and *C* were analyzed for this condition just as they were for normal excitation. The dashed curves in figure 4 show the fifth-harmonic voltages measured for the three different values of distribution transformer capacity. These data show that the harmonic voltages are more than doubled over the values obtained for the condition of normal excitations on all transformers.

In an actual system, these harmonic voltages are usually amplified more or less by the transmission line and transformer capacitances, so it is not uncommon to find voltages much higher than those shown in figure 4. Also, the magnetizing current required by induction motors and other "iron core" loads have their effect in increasing these voltages. In fact all loads with nonlinear impedance characteristics contribute to this phenomenon.

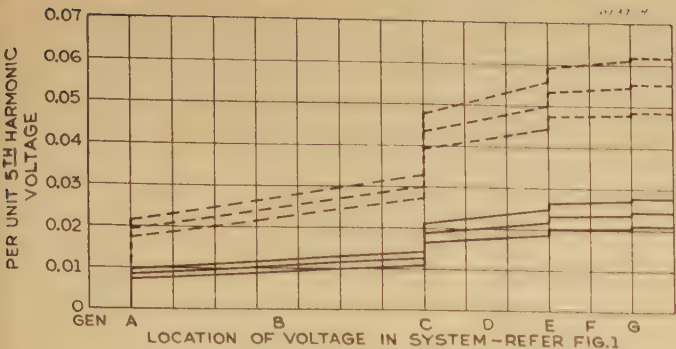


Figure 4. Magnitude of fifth harmonic voltage appearing in the hypothetical system studied

Solid curves—Normal excitation on all transformers

Dashed curves—1.1 per unit excitation on all transformers

Curves . . . . *A*. . . *B*. . . *C*
Ratio of Distribution
Substation Capacity. . . . . 1 . . . 2 . . . 3

The authors have studied test data taken on two systems that exhibited unusually high fifth-harmonic voltages. In these tests it was found that a general lowering of the voltage levels by approximately 10 per cent, resulted in a decrease of 50 per cent in the fifth-harmonic voltages.

On another occasion, severe overcurrents were being experienced due to the circuit being in *partial* resonance with capacitance. It was found that a decrease of only 4 per cent in the voltage feeding the affected area reduced the harmonic condition sufficiently to cure the difficulty.

Reduction of Harmonic Voltages Arising From Exciting Currents

In certain areas the application of shunt capacitors has been somewhat impeded due to these harmonic voltages. Resonance has occurred on occasion resulting in excessive fuse blowing. Also an occasional case of low-frequency induction in communication circuits has been experienced. Almost without exception these cases have been controlled by the fifth-harmonic or 300-cycle component. Therefore it is believed that if a method of reducing this component to a negligible amount was realized, the broad problem could be considered solved.

Use of Capacitors. Since capacitors have more or less exposed this harmonic condition in modern distribution circuits during the last few years, it seems paradoxical that they could be used to suppress these harmonic voltages. Such a method however is available and attention is directed to it in this paper since it is believed to be not very well known in this country. It has however been used successfully for several years in Japan[3] in the larger capacitor installations.

The scheme consists of putting a reactor in series with a group of capacitors. This reactor is proportioned in respect to the capacitors, so that the combination is in or near resonance with the fifth harmonic. The fifth-harmonic voltage is then effectively short-circuited at the point of application with the improvised resonant shunt. In fact it can be shown that it is reduced to a negligible amount in the surrounding area for a considerable radius. The amount of harmonic current that flows into this "harmonic short circuit" is equal to the voltage at that point before the equipment was applied divided by the system impedance viewed from that point. In general this current will not be so much since the harmonic voltage isn't large to begin with and further the system reactance is large, being increased by the order of the harmonic. It is interesting to reflect on the possibilities of this scheme when carried to a limit. If a sufficient number of these "harmonic short circuits" or resonant shunts were applied to a system, practically all of the fifth-harmonic current could be made to flow in short localized paths from the transformers to the shunts, thus practically eliminating the harmonic voltages from appearing, as described in the body of the paper.

A very important point to remember in this respect is that the normal, 60-cycle power-factor improvement afforded by the capacitors is not reduced by this series reactor. Since approximately a four per cent reactor is required for this application, the 60-cycle voltage on the capacitors is raised by this amount and the net available corrective kilovolt-amperes to the system is likewise increased by four per cent. If it is desirable from other considerations to practically eliminate the flow of harmonic current instead of the harmonic voltage, the reactor can be so proportioned to make a harmonic wave trap (equation 5 in appendix) out of the capacitor bank, and as before the normal 60-cycle correction afforded by the capacitors is increased by the reactor. Thus it is seen that power-factor and wave-form improvements can be obtained simultaneously by a single master stroke.

Reduction of Transformer Excitations

Reducing excessive overexcitations and providing the proper regulating equipment for voltage control would, of course, be in order where it could be justified. No doubt there are many transmission and substation transformers that could be operated at much lower densities if the distribution circuits were properly regulated.

The distribution transformers however, in general, cannot have their voltages reduced without accepting certain losses in revenue and a reduction in the quality of service rendered. As described in more detail below under power factor, it is well known that in the last several years the transformer secondary voltages have been creeping up from 110 to 125 volts and even higher. Obviously many older-type transformers originally designed for 110 volts are now operating 10 per cent and even 15 per cent overexcited. In view of these trends, it is believed that a policy of more closely scrutinizing the replacement of obsolete equipment with up-to-date designed-for-the-service apparatus would prove a sound investment.

Table I

Equipment Identification Refer Figure 1	Type of Equipment	Per Unit Rating	Per Unit Reactance on Own Base	Per Unit Exciting Current on Own Base: Normal Excitation	Per Unit Exciting Current on Own Base: 1.1 Per Unit Excitation
Generator	Sine-wave voltage source	Infinite	0		
A	Transformer—step up	1.0	0.08	0.045	0.08
B	High-voltage transmission line	1.0	0.05		
C	Transformer—step down	1.0	0.08	0.045	0.08
D	Medium voltage distribution	1.0	0.05		
E	Three substation transformers	0.5 ea.	0.05 ea.	0.04	0.07
F	Three lines—four-kv feeders	0.5 ea.	0.05 ea.		
G	Transformer equivalent of total connected distribution transformers, Case *A*	0.5	0.025	0.02	0.03
	Case *B*	1.0	0.025	0.02	0.03
	Case *C*	1.5	0.025	0.02	0.03

Cases *A*, *B*, and *C* differ only in the ratio of connected distribution to substation transformer capacity, of which the ratios are 1, 2, and 3, respectively.

System Power Factor and Overexcitation of Transformers

The past several years has seen in general a marked decrease in over-all system power factor. The deleterious effects of poor power factors coupled with increased loads upon system capacity and voltage are well known. The answer to the questions inquiring into the cause of this decrease in power factor has generally been "motorized appliances, air conditioning, gaseous-tube lighting, etc." These factors beyond a doubt have had their effect, but it is interesting to speculate on the effect of transformer magnetizing currents, especially when the transformers are overexcited.

Not so long ago it was the practice to serve a customer with 110 volts, or its equivalent at a higher level. Later the standard was considered to be 115, so taps were changed and general levels raised to accommodate this change in philosophy. During the last few years this meter-box voltage has risen to 120 which represents approximately a ten per cent increase over the original 110. In fact in many places it is necessary to hold 125 volts or even higher at the transformer in order that the load be served at rated voltage. During the evolution of this practice of gradually raising the voltage, new transformers designed for the voltage were of course being added to accommodate load growth, but, most of the older equipment obviously remained on the system. Thousands of kilovolt-amperes of transformers on most systems today that were built to operate at a normal density corresponding to 110 or 115 volts, are actually being operated at or above 120 volts. Transformers in general can stand this duty because they are designed for it, but obviously they must draw larger magnetizing currents to accommodate the increased flux requirements.

The effect on the magnitude of the total exciting current required by all the transformers in the circuit of figure 1 due to overexciting the transformers ten per cent is clearly seen by the figures in table II. Here it is seen that the exciting-current requirements are practically doubled, for the overexcited condition. For the case at hand, reactive kilovolt-amperes approximating 40 per cent of the system rating may be required merely to excite the transformers. These figures may of course be off a little quantitatively, but they are believed to be sufficiently accurate qualitatively to show that system power factor can be materially reduced by operating transformers above their normal densities. It is well known that many times a generator must be kept on the line merely to supply reactive, and the overexcited transformers may well be the cause of the requirement in some cases.

The transformer, however, should not be indicted for this. Magnetic saturation is a fundamental characteristic of iron and must be more or less accepted in the interests of economy. However if transformers were operated at their normal densities and proper regulating equipment were applied along with a properly designed distribution system, these exigencies would not arise. Admittedly this is a Utopia impossible to attain, but it is believed that with these facts known and understood, more attention to the problem can be intelligently and profitably applied. Magnetic saturation and magnetizing reactive kilovolt-amperes is something with which the engineer must live—hence it behooves him to treat it with respect and design his systems accordingly. It is believed that the replacement of lots of these older, overexcited distribution transformers with up-to-date designs and/or the use of appropriate regulating equipment could be justified from the standpoint of decreased losses and decreased magnetizing currents alone. One should not conclude from this discussion that power-factor improvement be attained by reducing voltages, but the over-all condition can be greatly improved by properly regulating the voltage. In this respect the authors are acquainted with one distribution system in which voltage regulators were systematically applied and much to the surprise of the engineer, the power factor coincidentally was improved from 70 to 85 per cent.

Table II

Total Per Unit Exciting Current Required by Transformers in Circuit of Figure 1 for Various Excitations and Ratios of Distribution to Substation Transformer Capacity. Kilovolt-Ampere Base = 1.0

Capacity ratio	1/1	2/1	3/1
Normal excitation	0.18	0.21	0.24
1.1 per unit excitation	0.31	0.35	0.40

Reference to the preceding section on reduction of harmonic voltages should be made for further discussion of reactive control. In this section the use of capacitors is described for improving wave form distortions due to saturation and at the same time provide leading kilovolt-amperes for power-factor improvement. It is interesting at this point to note that since shunt capacitors increase their kilovolt-ampere output as the square of the applied voltage, the increased exciting current kilovolt-amperes required by transformers at increased voltages can, to a certain extent, be automatically compensated for in this manner. These points are mentioned since it is profitable and desirable to operate distribution systems at 120 volts and higher, thus making it necessary that the engineer be provided with the proper equipment to cope with the conditions resulting therefrom.

Appendix. Use of an Equivalent Circuit for Determining Flow of Harmonic Magnetizing Currents

Consider the circuit shown in figure 2 which is the equivalent diagram of a transformer connected to a pure sine-wave voltage source with a harmonic generator in the magnetizing branch for furnishing the harmonic magnetizing currents. The circuit connected by the switch represents a set of capacitors, x_{c1}, in series with a reactor x_s and a set of capacitors, x_{c2}, with no reactor.

Consider the switch open, and the transformer excited from the pure 60-cycle source. Since there is magnetic saturation in the x_m branch, certain harmonic currents will flow and these can be represented as being driven through the system by a harmonic generator located in the x_m branch. Then letting

i_n = harmonic current
x_1 = 60-cycle reactance of system up to transformer plus transformer primary reactance
x_2 = same on secondary side
n = order of harmonic

the harmonic voltage at the switch can be written as

$$e_n = i_n n x_1 \tag{1}$$

This reasoning assumes that the magnitude of i_n is determined solely by the applied 60-cycle excitation sine wave of voltage and neglects the infinitesimal amount that flows due to the appearance of a small harmonic voltage at the transformer terminals.

Assume further that the reactor x_s and the capacitor x_{c1} are proportioned so that

$$n x_s = x_{c1}/n \tag{2}$$

then the harmonic current meets zero impedance when the switch is closed.

Closing the switch results in the flow of i_n' through the switch of the magnitude

$$i_n' = i_n \frac{n x_1}{n(x_1 + x_2)} \tag{3}$$

and substituting equation 1

$$i_n' = \frac{e_n}{n(x_1 + x_2)} \tag{4}$$

Thus, to determine the readjustment of the flow of the harmonic current due to a resonant shunt or a "harmonic short circuit" it is merely necessary to divide the voltage at the point of application by the

Testing of Elevator Buffers by Electrical Means

E. E. KIMBERLY
ASSOCIATE AIEE

THE purpose of an elevator buffer is to stop the elevator in event it reaches the bottom of its hoistway out of control. To prevent injury to its occupants, the rate of stopping must not exceed $2^1/_2$ times gravity or about 80 feet per second per second for more than $^1/_{25}$ second. The tests on a buffer should be such that the velocity at which the elevator strikes the buffer and the rate of deceleration at every point in the piston stroke may be determined. If the buffer contains oil, it is important for the designer to know also the oil pressure at every point in the stroke.

Methods Formerly Used

The test method found most satisfactory up to this time employs a platen, driven directly from the buffer piston or by the elevator, on which a tuning-fork-driven stylus records the distance traveled by the platen during successive cycles of the fork vibrations. From this record the velocity and deceleration are calculated. A modified steam-engine type of pressure indicator operates another stylus on the same platen to record the varying oil pressure.

Paper 40-147, recommended by the AIEE committee on instruments and measurements, and presented at the AIEE Middle Eastern District meeting, Cincinnati, Ohio, October 9–11, 1940. Manuscript submitted February 25, 1938; made available for preprinting August 23, 1940.

E. E. KIMBERLY is associate professor of electrical engineering, Ohio State University, Columbus.

In methods previously used, the tuning fork vibrates with constant frequency while the platen velocity varies with that of the car. This arrangement produces a record on which the highest velocity of fall produces the fewest cycles per inch on the record. With the electrical method described, the highest velocity of fall is recorded with the greatest number of cycles per inch of record and the accuracy of the calculations of retardation are best therefore when the velocity of fall is highest. Inasmuch as dangerous deceleration rates are more likely to occur early rather than late in the stroke of a buffer reasonably well designed, it is better to achieve accuracy of measurement at the higher rather than at the lower velocities.

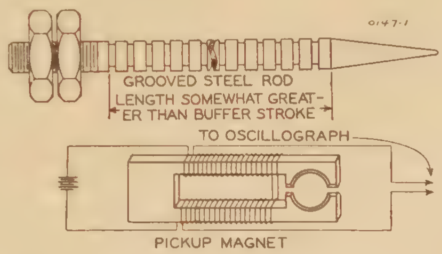


Figure 1. Pickup magnet and grooved iron inductor rod

Determination of Velocity and Deceleration

To determine the striking velocity of the elevator car, a magnetic pickup coil and grooved iron rod shown in figure 1, is used. The rod is mounted vertically on the car, attached by its upper end so that as it falls with the car it passes through the bore of the pickup magnet which is mounted on one of the guide rails. The magnet has an exciting winding of about 200 turns of number 18 magnet wire and also a secondary coil of about the same number of turns which is connected to a high-sensitivity galvanometer element of an oscillograph. As the rod drops through the bore of the pickup magnet, the changes in permeance of its magnetic circuit, caused by the grooves in the rod, vary the magnetic flux and induce in the secondary coil an alternating voltage, which is recorded by the oscillograph. One six-volt storage battery serves to excite the pickup magnet. A similar rod and pickup coil may also be used on the buffer piston itself if the performance of the piston must be known.

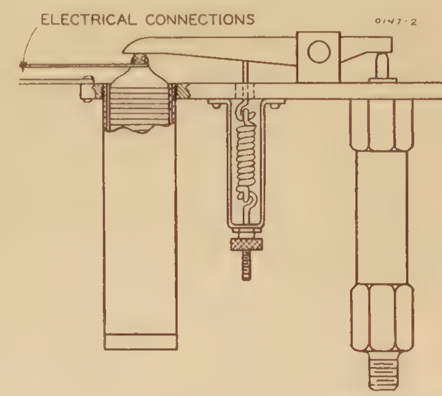


Figure 2. Carbon-pile oil-pressure gauge

A 60-cycle voltage wave on the same oscillogram as the varying-frequency alternating voltages of the pickup coils is of convenience in timing.

In calculating the velocity of the car at any point in its fall the following formula may be used:

$$V=\frac{5NL\times m_{60}}{m_r}$$

in which

V = velocity of fall in feet per second
N = number of cycles scaled on pickup record on oscillogram

---

driving point impedance of the circuit viewed from that point. This fundamental principle has been used for years by engineers in making short-circuit calculations. It can be shown, within the assumptions, that this method of calculating the flow of short-circuited harmonic current in a complicated network, is correct. The demonstration above for a simple circuit is given in the interests of clarity.

It is interesting to note that if x_s is proportioned so that

$$nx_s=x_{c1}/n+x_{c2}/n \qquad (5)$$

a wave trap is formed by the network, which presents infinite (neglecting losses) impedance to the harmonic thus preventing the flow of harmonic current.

Either of these reactor schemes can be used in capacitor applications depending upon the objective. The condition imposed by equation 2 reduces the line harmonic voltage to zero whereas the conditions represented by equation 5 reduces the line harmonic current to zero.

References

1. SURVEY OF POWER SYSTEM WAVE SHAPES, Engineering Reports of the Joint Subcommittee on Development and Research, volume 2, pages 189–290.

2. THE WOUND-CORE DISTRIBUTION TRANSFORMER, E. D. Treanor. AIEE TRANSACTIONS, 1938 (November section).

3. ON THE PHASE ADVANCEMENT AND THE WAVE FORM IMPROVEMENT DUE TO STATIC CONDENSER, K. Kitagawa and I. Tanaka. *Journal* of the Institute of Electrical Engineers of Japan, volume 56, number 532, 1936.

IMPROVEMENT OF VOLTAGE WAVE FORM BY STATIC CONDENSERS FOR POWER FACTOR IMPROVEMENT, K. Kitagawa and I. Tanaka. *Electrotechnical Journal*, August 1937.

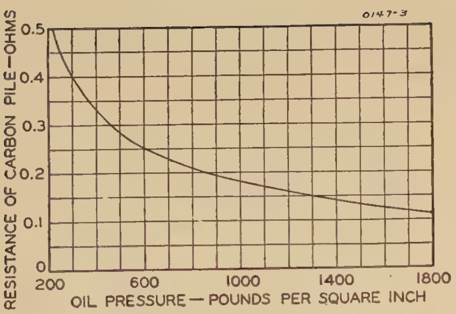


Figure 3. Typical carbon-pile pressure calibration curve

L = distance in inches between centers of adjacent grooves on rod

m_{60} = millimeters (or inches) per cycle measured on the 60-cycle timing wave

m_r = millimeters (or inches) measured over N cycles at chosen point on pickup record. When the frequency is high, three or four cycles should be used. When the frequency is low, two cycles are sufficient.

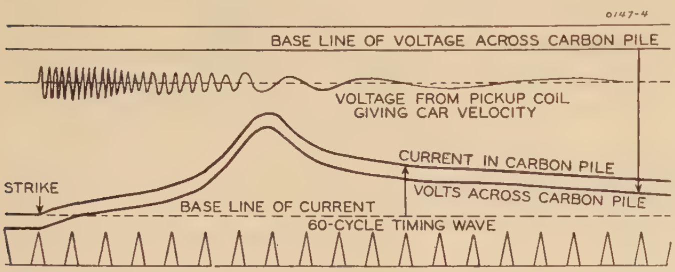


Figure 4. Typical oscillogram from which the performance of the buffer is calculated

To obtain the curve of deceleration versus inches of stroke it is necessary to plot a curve of velocity versus time from figure 5. The slope of this curve at any point is then the rate of change of velocity from which the curve of deceleration of figure 5 is plotted.

Measurement of Oil Pressure

The oil-pressure gauge consists of an oil-pressure cylinder and a carbon pile mounted together with a rocking beam connecting them as in figure 2. The carbon pile consists of 42 carbon disks each of which is $^1/_8$ inch thick and $1^1/_2$ inches in diameter. The disks were ground to a true surface on each side as far as possible. The disk pile is enclosed in a paper tube and inserted in a brass tube shown in figure 2. The rocking beam by which the pressure at the piston is transmitted to the carbon pile has a lever arm ratio of $1^1/_2$ inches to $4^1/_2$ inches. Because the long end of the beam moves only $^1/_{16}$ inch with the greatest oil pressure encountered, inertia effects are reduced to a satisfactory minimum.

The carbon pile is calibrated in resistance versus pressure. The current through the carbon pile and the voltage across it are both recorded on the oscillograph film so that the resistance may be calculated and the pressure determined for any point in the piston stroke. A calibration curve is shown in figure 3. Figure 4 shows a sketch of a typical oscillogram. Figure 5 shows the final curves of performance of the buffer.

Difficulties to Be Avoided

To obtain sufficient voltage in the pickup magnet coil to operate the oscillograph element without interposing an amplifier, the hole in the magnet should not exceed three-fourths inch in diameter when a five-eighths-inch grooved rod is used. Grooves one-eighth inch long, one-eighth inch deep and spaced three eighths inch apart were found quite satisfactory.

If there is no guide provided for the suspended rod, the impact of the car on the buffer piston may cause the rod to deflect and strike the pickup magnet instead of its hole. A long brass point fitted to the rod attached to the car proved helpful in guiding that rod through the pickup magnet in its fall. A fiber bushing in the pickup magnet hold (not shown in figure 1) was found helpful in guiding the rod. It was also found advisable to mount the magnet so that it was free to move laterally to follow any swinging of the rod.

In comparison with electric strain gauges recently developed the carbon pile has the advantage of requiring no amplifier or source of high-frequency voltage for oscillographic recording.

Summary

The curves of figure 5 are typical of those obtainable by the electrical apparatus described. Inasmuch as the oil-pressure indicator was connected to the bottom of the buffer cylinder, there was a short time interval between the instant of maximum pressure as shown on the pressure gauge and the maximum deceleration. This time interval is that required for the high-pressure wave to travel through the oil from the piston to the gauge. This difference in time demonstrates the elasticity of the light transformer oil used.

The accuracy of this method is satisfactory for all existing test codes.

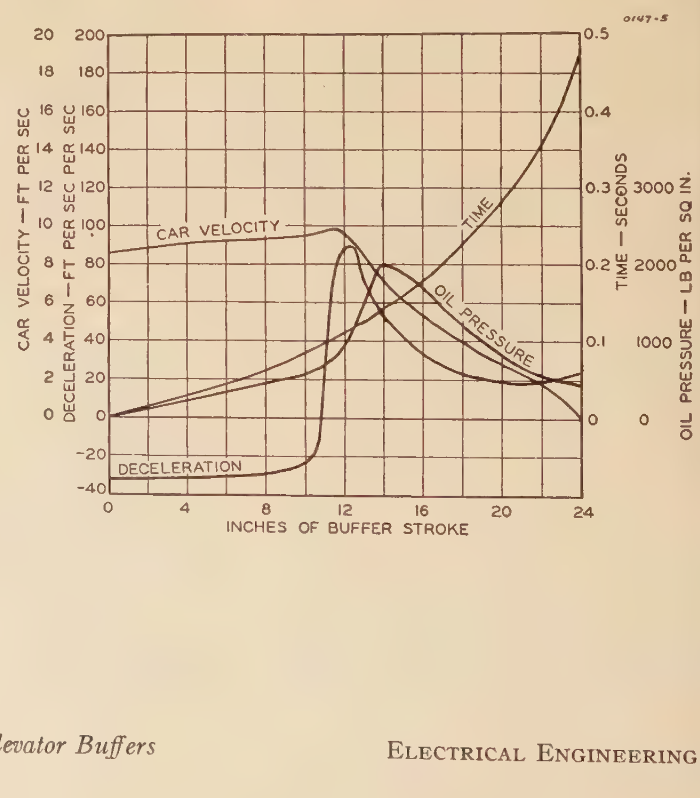


Figure 5. Typical performance curves of a buffer with poor workmanship or of poor design

Single-Phase Induction-Motor Performance Calculation

F. S. HIMEBROOK
MEMBER AIEE

IN the manufacture of electrical machines it is always desirable to calculate the performance of a machine before its construction to determine whether or not it will meet the specifications. The usual methods of predetermining performance involve the use of either a circle diagram or an equivalent circuit and since either of these methods involves considerable work there are always possibilities that errors may be introduced by slight mistakes in construction, measuring, etc. It was believed that if a method could be developed by which the quantities necessary for performance calculation could be given in the form of a set of curves considerable time might be saved provided that the accuracy so obtained was of the same degree as that given by other methods.

This paper describes the development of a method which may be used to plot, as families of curves, the quantities necessary for the performance calculation of single-phase induction motors. Consideration is first given to a circle diagram which is known to give accurate results when used to calculate the performance of motors of this type. It is then shown that all of the quantities involved in the calculation of performance are dependent upon certain ratios of the fundamental motor constants and not upon the absolute values of the constants. This means that it is not necessary to draw a new circle diagram for each motor and any diagram may be used in any number of cases as long as the fundamental relations are held constant. Thus if a number of diagrams are made for different ratios of motor constants the data required for performance determination may be evaluated and plotted in the form of curves which may be used to take the place of the circle diagrams. Such curves are at least as accurate as the diagrams they replace because slight errors in reading values become apparent when plotted and tend to be either minimized or averaged out.

Besides the motor characteristics in the usual operating range it is always desirable to know the value of the maximum torque. It was found that the information required for the calculation of the maximum torque might be determined by making use of the diagrams previously described and a method of plotting the necessary quantities in the form of curves is given.

Extension of the methods given for the calculation of the performance of polyphase motors is shown to be possible and is discussed briefly.

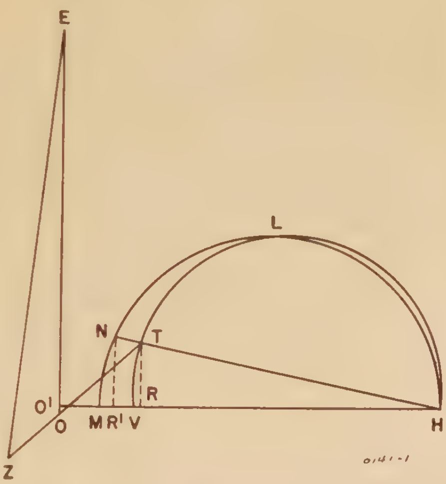


Figure 1. Circle diagram used in determining performance of single-phase induction motors

The Circle Diagram

The circle diagram used (figure 1) is the one given by Branson[1] in his paper which explains the operation of the single-phase motor by the cross-field theory. The methods of constructing this diagram and of using it are included in appendices I and II.

By reference to appendix I it will be seen that since $O'H$ is a constant and since $O'M$ is a variable dependent only upon K_r (defined in appendix I), that the value of MH and the semicircle $MNLH$ are also functions of only K_r. Thus, for any particular value of K_r this part of the diagram is fixed.

In a like manner, the value of MV is determined by the value of K_r and point V located accordingly. The value of LH is dependent upon both K_r and the ratio r_2/X but for any particular values of these two quantities the point L is definitely located. Because points V, L, and H are all located and because all three points must lie on the circumference of one circle the center of this circle is located at the intersection of the perpendicular bisectors of lines VL and LH. After the center has been located arc VLH may be swung.

Actually the line OO' is not constant, as assumed in appendix I, but varies with the motor under consideration. However the assumed value is sufficiently close to the average value calculated for normal motors that the error introduced by this assumption is very slight. Having located point O the directions of lines OT are defined.

By definition

$$OZ=(S_1r_1/S_e)\times OT \tag{1}$$

and by substituting equivalent values for S_1 and S_e we may change this to the form

$$OZ=\frac{(E/10X)}{(E/OE)}\times r_1\times OT=\frac{(OE=10)}{10X}\times r_1\times OT=\frac{r_1}{X}\times OT \tag{2}$$

giving a solution for the length OZ which is a direct function of r_1/X.

Thus it is seen that the entire diagram is dependent only upon K_r, r_2/X and r_1/X and that the performance of all motors having the same values for these quantities will be identical. Since this is true it is evident that with the use of only a relatively small number of diagrams it is possible to determine the performance of a wide variety of motors. We may also proceed one step farther and plot the values of OT, MT, etc., in the form of curves and so have all of the information required for performance calculation in a convenient form. In carrying out this work for a given value of K_r it will be found convenient to plot the values of OT, MT, etc., against the length of MN since this value remains constant for a given value of K_r regardless of the ratios r_1/X and r_2/X.

This method of plotting the curves may be seen by reference to figures 2 and 3. In some cases all of the values for the

Paper 40-141, recommended by the AIEE committee on electrical machinery, and presented at the AIEE Middle Eastern District meeting, Cincinnati, Ohio, October 9–11, 1940. Manuscript submitted July 13, 1937; made available for preprinting August 12, 1940.

F. S. HIMEBROOK is electrical engineer in charge of laboratories, Master Electric Company, Dayton, Ohio.

The writer wishes to thank The Hoover Company for permission to publish this paper, the material for which was developed while a member of their engineering department.

1. For all numbered references, see list at end of paper.

ranges of r_2/X considered do not differ appreciably and so only one value has been shown. For example the values of TR as shown all lie within about 0.01 inch of the value shown and since errors in measurement might have been at least ± 0.01 inch it was not believed necessary to attempt to show any more than one curve.

In calculating the performance the procedure followed is that outlined in appendix II.

Performance Calculation Using Curves

In the final analysis the utility of a method lies in the accuracy of the results obtained. The performance of a one-fourth-horsepower single-phase induction motor was calculated by the use of the curves described herein and the methods described in appendix II, and is shown with the actual test data for this motor in table I. Examination of this table shows that the calculated and measured results do not differ widely in any respect.

Determination of Maximum Torque

It was known that the point corresponding to maximum torque lay on arc VTL (figure 1) somewhere beyond, but near to, the center of arc VTL. To locate this point precisely would have required the choosing of several points, calculating the data for each point, and then finding the desired point by the process of elimination. It was found, experimentally, that the point corresponding to the maximum torque lay almost midway between the center of arc VTL and the point of tangency between the arc VTL and a line drawn parallel to ML. The point found in this manner located the point of maximum torque closely enough for all practical purposes.

The values of OT, MT, etc., corresponding to the point of maximum torque may also be read and plotted in the form of curves. It was found convenient to plot these values against K_r as shown in figures 4 to 7, inclusive.

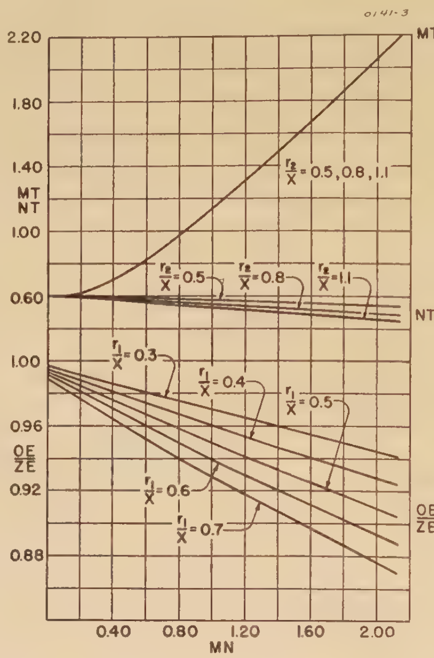


Figure 3. Curves showing data required for performance calculation of single-phase induction motors. (K_r = 0.93)

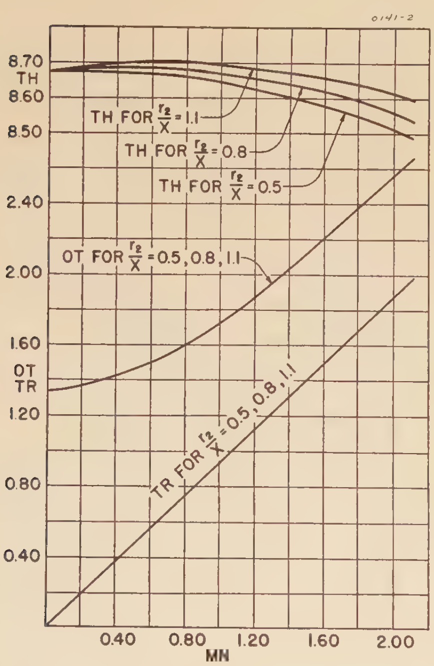


Figure 2. Curves showing data required for performance calculation of single-phase induction motors. (K_r = 0.93)

The locus of the current vector in an ideal motor follows a circular path but this ideal is deviated from in the case of an actual motor. Usually the circular locus is accurate for points in the normal operating range but some deviation is often noted when calculating the maximum torque. It has been found[1] that the maximum torque as obtained by a brake test is only about 0.92 of the calculated value and so it is necessary to multiply the calculated torque by 0.92 to secure the value to be expected in an actual motor. Aside from this, calculation of the maximum torque is carried out in the same way as for any other point. (See appendix II.)

When the calculation was made upon the motor previously considered the indicated maximum torque was found to check closely (see table I) with the measured value.

Extension of Method to Polyphase Motors

The same diagram may be used to derive a similar set of curves for polyphase motors. For this work MH is again equal to $10K_r$ and the length OO' becomes 0.05 inch for all practical purposes. The inner circle $VTLH$ does not exist and point T lies on $MNLH$. For use with polyphase motors the values of OT, MT, TR, OZ, and ZE are required. These correspond to ON, MN, NR', OZ, and ZE of the single-phase diagram (figure 1).

Thus without a great deal of additional work a set of polyphase curves might be obtained. However, these curves are not believed to be in as usable a form as the "*a-b-c*" curves described by Branson.[2]

Discussion

It was assumed, in deriving the material contained herein, that the core loss OO' could be given as 0.10 inch in all work and that the ratio of the saturation factors in the main and cross fields was unity. Some such assumption was required or a complete set of curves would have been required for each value of core loss and each ratio of saturation factors. A number of tests were computed and indicated that these assumptions might readily be made. In all use to date these assumptions have been found sufficiently accurate to warrant their use.

The ranges of values of K_r, r_1/X, and r_2/X shown in the sample curves are believed great enough to cover most ordinary motors. As special cases are encountered their data may be recorded and used to build up a more extensive set of curves.

Table I. Comparison of Measured and Calculated Characteristics of a One-Fourth-Horsepower Single-Phase Induction Motor

Quantity	Measured	Calculated
r_1	1.29 ohms	1.30 ohms
r_2	2.51 ohms	2.41 ohms
X	3.60 ohms	3.60 ohms
X_0	51.2 ohms	50.2 ohms
K_r	0.929	0.932
Full-load speed	1,747 rpm	1,737 rpm
Full-load current	4.82 amp	4.81 amp
Full-load efficiency	64.3 per cent	61.5 per cent
Full-load power factor	56.7 per cent	57.2 per cent
Full-load input	292 watts	302 watts
Maximum torque—in per centrated load torque	310	304

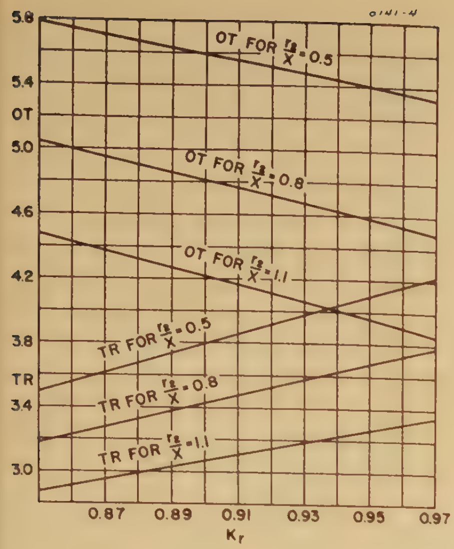


Figure 4

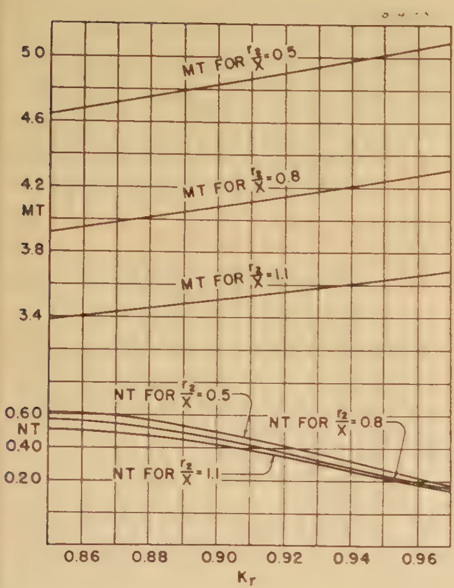


Figure 5

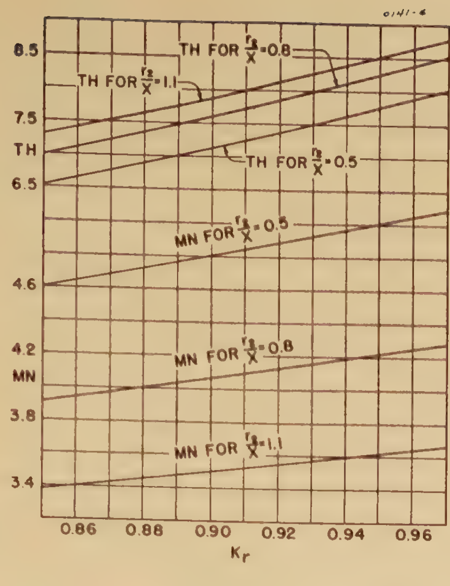


Figure 6

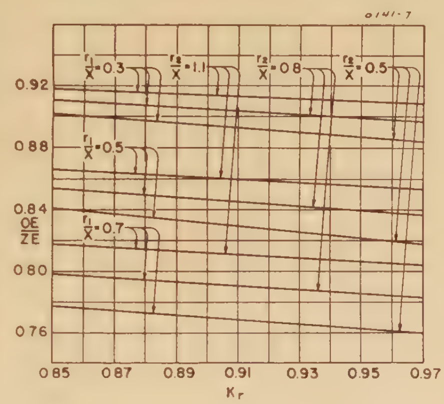


Figure 7

Figures 4–7. Curves showing data required for calculation of the maximum torque which may be expected of a single-phase induction motor

The results obtained by the use of the curves indicate that when the original work is carefully carried out that considerable time may be saved and results are obtained which are as accurate as might usually be obtained by the construction of a special diagram for each motor. In addition, when the curves are plotted any but the most trivial errors are immediately made evident because any errors (except consistent errors) are shown by irregularities in plotting.

Appendix I

Construction of Circle Diagram

Before constructing the circle diagram (figure 1) it is necessary to know the values of the following quantities:

r_1 = stator resistance, ohms
r_2 = rotor resistance, ohms, referred to the stator

Both r_1 and r_2 represent the resistances when the motor is at its normal operating temperature. For a motor designed for a 40-degree centigrade rise, the hot resistance is 1.15 (cold resistance).

X = total leakage reactance, ohms
X_0 = no load reactance, ohms

$$K_p = \frac{\text{permeance of mutual path}}{\text{permeance of mutual and primary leakage paths in parallel}}$$

$$K_s = \frac{\text{permeance of mutual path}}{\text{permeance of mutual and secondary leakage paths in parallel}}$$

$K_r = K_pK_s = (X_0 - X)/X_0$
E = impressed electromotive force, volts

To construct the circle diagram proceed in the following manner. Lay off the horizontal line $O'H = 10$ inches. (Any length may be used but 10 inches is probably the most convenient. The line OE which is passed perpendicularly through $O'H$ at O' is also made equal to 10 inches for convenience.)

Calculate the voltage and current scales.

S_e = voltage scale, volts per inch, $(=E/10)$
S_1 = stator current scale, amperes per inch, $(=E/10X)$
S_2 = rotor current scale, amperes per inch, $(=S_1/K_p)$

Lay off

$$\left\{\begin{array}{l} i_m \quad = E/X_0 \\ O'M = E/S_1X_0 \end{array}\right. = 10(1-K_r)$$

Using MH as a diameter, construct the semicircle $MNLH$.

$$i_{ms} = \frac{i_mK_r}{2-K_r} \times \frac{\text{saturation factor (cross field)}}{\text{saturation factor (main field)}}$$

$$\text{Calculate } MV = \frac{E}{S_1X_0} \times \frac{K_r}{2-K_r} \times \frac{\text{saturation factor (cross field)}}{\text{saturation factor (main field)}}$$

where the saturation factor is defined as

$$\frac{\text{total ampere turns required}}{\text{ampere turns required for air gap alone}}$$

(The saturation factors for the data shown in the curves have, for convenience, been assumed equal. This is practically true for most motors.)

Locate the locked point L. The distance $LH = MH \sin^{-1} (\tan r_2/X)$

Construct a circle passing through V, L, and H

Construct $OO' = 0.10$ inch (OO' is the main field iron loss current and is equal to main field power loss/ES_1. Its value in most normal motors lies very close to 0.10 inch)

From O lay off $OE = 10$ inches

Choose various points T, draw lines NTH and OT, extending the lines OT to the left of OE a distance $OZ = \{(S_1r_1)/S_e\} \times OT$

Draw lines ZE.

Appendix II

Calculation of Performance Data

For each point T the following procedure is used.

Secure curves (figures 2 and 3) for desired value at $K\gamma$. Select values of MN; read values of TH, OT, and TR for proper r_2/X from figure 2; read values of MT and NT for proper value of r_2/X and OE/ZE for the proper value of r_1/X from figure 3.

1. OT—from figure 2 for proper value of K_r
2. MT—from figure 3 for proper value of K_r
3. MN—selected value, figures 2 and 3
4. NT—from figure 3 for proper value of K_r
5. TH—from figure 2 for proper value of K_r
6. TR—from figure 2 for proper value of K_r

The Cross-Field Theory of the Capacitor Motor

A. F. PUCHSTEIN
MEMBER AIEE

T. C. LLOYD
ASSOCIATE AIEE

ANALYSES of the capacitor motor operation date back to the 1920's, a pioneer effort being that of Brüderlin[1] in Europe. Work by Bloch,[2] Biermanns,[3] and others antedates that of Morrill[4] in this country whose analysis has been widely used. All of these have been based on the double revolving field theory, being extensions of that theory to the usual single-phase induction motor.

The cross-field theory has been successfully applied to plain single-phase induction motor analyses by Sumec,[5] Arnold and LaCour,[6] Steinmetz,[7] West,[8] and others, but heretofore no application of this theory has been made to the capacitor motor. The present paper is an exposition of such an analysis.

For the present purpose only two fundamental variations appear in the treatments of the cross-field theory. These concern the speed electromotive forces, built up by rotation of the rotor conductors through the rotor leakage fluxes. To elaborate on this idea, one may take the view that for the same saturation when locked and running, the machine leakage reactance is independent of rotation and that no revolving harmonic fields are present. Of the usual components of leakage flux, namely, slot, zigzag, end, and differential, the stator slot and end connection leakage are stationary in space. By the same reasoning the rotor slot and end connection leakage fluxes rotate with the rotor in space; the zigzag and differential leakage fluxes vary their distribution more or less with different rotor positions, although tacitly an average is assumed. Arnold and West imply that more accurate results are obtained if the assumption is made that the rotor leakage fluxes stand still in space, as opposed to the Steinmetz view that they move with rotation. As a working basis for the former viewpoint which will be used here, the slot, zigzag and end connection components of rotor leakage flux will all be considered as stationary, making up X_2. The differential leakage component should be charged to the stator.

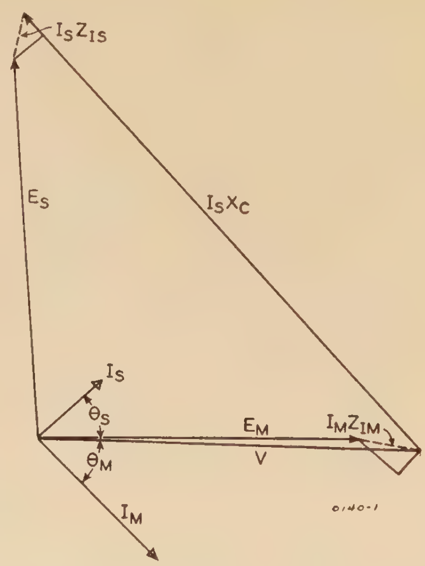


Figure 1. Vector diagram showing stator currents and voltage components

Paper 40-140, recommended by the AIEE committee on electrical machinery, and presented at the AIEE Middle Eastern District meeting, Cincinnati, Ohio, October 9–11, 1940. Manuscript submitted July 10, 1938; made available for preprinting August 12, 1940.

A. F. PUCHSTEIN is consulting engineer, Springfield, Ohio, and T. C. LLOYD is chief engineer of Robbins and Myers, Inc., Springfield, Ohio.

1. For all numbered references, see list at end of paper.

Considerable difference of opinion exists regarding the relative merits of the two classical theories for explaining single-phase induction-motor phenomena. It is not the intention of the present writers to advance the cross-field theory as being wholly superior. Each method has certain advantages and defects. For instance the cross-field theory is blind to the existence of two separate skin effects in rotor conductors and to a pulsating torque superposed on a steady torque. (This latter difficulty could be avoided by the use of instantaneous instead of vector quantities.) But differences in saturation and core losses in the two axes are much easier to visualize with the cross-field theory. And as for its application to the capacitor motor, certain other advantages will be developed and contrasted later.

Fundamental Relationships

The relationship on which the equations are based can be stated briefly as follows (assuming that the stator windings are in space quadrature):

1. The voltage applied to the main winding overcomes a local stator impedance drop and the counter electromotive force built up by the mutual flux of the main axis.

2. The stator current is the resultant of a load component reflected by transformer action from the rotor and a main-axis magnetizing current which may or may not contain an iron loss component.

3. The voltage applied to the quadrature winding (called here the start winding) overcomes the local stator impedance drop of that winding, the reactance or impedance

---

7. OE/ZE—from figure 3 for proper value of K_r
8. $MN \times r_2/X$
9. $NT \times r_2/X$
10. $TH-(8)$
11. $\text{rpm} = \sqrt{\dfrac{(10)}{(5)}} \times$ synchronous speed (approximately)

$$= \sqrt{\frac{(10)^2+(9)^2}{(5)\times(10)}} \times \text{synchronous speed (exact formula)}$$

12. Primary amperes $= (1) \times (7) \times S_1$
13. Secondary amperes $= (2) \times (7) \times S_2$
14. Secondary copper loss (cross field) $= (i_{ms}/K_p)^2 \times r_2 \times \{(11)/\text{syn. rpm} \times (7)\}^2$
15. Secondary copper loss (main field) $= (13)^2 \times r_2$
16. Iron loss (cross field) $= 0.45$ (polyphase iron loss)
17. Friction and windage loss = previously determined
18. Iron loss (main field) $= 0.50$ (polyphase iron loss)
19. Primary copper loss $= (12)^2 \times r_1$
20. Secondary input $= (7)^2 \times (6) \times E \times S_1$
21. Total input $= (18) + (19) + (20)$
22. Total losses $= (14) + (15) + (16) + (17) + (18) + (19)$
23. Output $= (21) - (22)$
24. Torque (ounce-feet) $= 112.7 \times (23)/(11)$
25. Efficiency $= (23)/(21)$
26. Input, volt-amperes $= (12) \times E$
27. Power factor $= (21)/(26)$

Bibliography

1. SINGLE-PHASE INDUCTION MOTORS, W. J. Branson. AIEE TRANSACTIONS, volume 31, 1912, pages 1749–87.

2. POLYPHASE INDUCTION MOTOR PERFORMANCE CALCULATION, W. J. Branson. AIEE TRANSACTIONS, volume 49, 1930, pages 319–28.

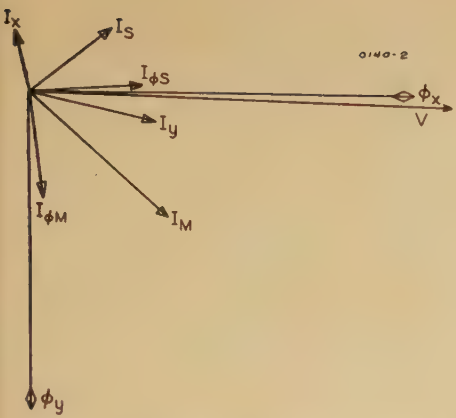


Figure 2. The stator current components and the flux vectors

drop of the capacitor in series with the winding, and the counter electromotive force built up by the mutual flux of the cross axis.

4. The stator current of the cross axis is the resultant of a load component reflected by transformer action from the rotor, and a start or cross axis magnetizing current similar to that of the main winding, but usually differing in magnitude.

5. In the rotor, the main or y-axis current results from two electromotive forces:

(*a*). The transformer voltage, opposite in phase to the stator counter electromotive force but of the same magnitude if the rotor constants are all considered in main winding terms.

(*b*). A speed voltage, resulting from the rotor conductors cutting the cross-axis mutual flux, and (as suggested by West and Arnold) the leakage flux of the rotor as well. By Kirchoff's law the vector sum of these voltages and the rotor impedance drop caused by the main axis current, equals zero.

6. In the start or x-axis of the rotor, two electromotive forces, similar to those listed above, are present:

(*a*). A transformer voltage opposite in phase to the cross-axis counter electromotive force but different in magnitude by the ratio of transformation between start winding and rotor, or start and main windings.

(*b*). A speed voltage resulting from cutting the main winding mutual and rotor leakage fluxes.

The vector sum of these voltages and the rotor impedance drop of the cross-axis rotor current equals zero.

The four fundamental equations are then (see list of symbols):

Main axis: Stator:

$$Z_M(I_M-I_y)+I_MZ_{IM}=V \qquad (1)$$

Start axis: Stator:

$$Z_S(I_S-I_X)+I_S(Z_{IS}+Z_C)=V \qquad (2)$$

X-axis: Rotor:

$$\frac{Z_S}{a}(I_S-I_X)+jS[-Z_M(I_M-I_y)+jI_yX_2]=aZ_2I_x \qquad (3)$$

Y-axis: Rotor:

$$-Z_M(I_M-I_y)+jS\left[-\frac{Z_S}{a}(I_S-I_X)+jaI_xX_2\right]=-I_yZ_2 \qquad (4)$$

These equations are extensions of West's[8] equations for the cross-field theory applied to the plain single-phase induction motor. The terms I_yX_2 and aI_xX_2 in equations 3 and 4, respectively, represent the added effect on the speed electromotive forces of cutting the rotor leakage fluxes. If these are dropped, the fundamental equations reduce to a form which Steinmetz's single-phase motor equations would yield.

By substitution, the stator components of the rotor currents, I_y and I_x, can be eliminated in these four equations, leaving two in terms of the two components of stator current. For further convenience in obtaining a final solution by determinants, the coefficients of these currents can be represented by the A, B, and C constants as shown below. Then:

$$A_1I_M+B_1I_S=C_1 \qquad (5)$$

$$A_2I_M+B_2I_S=C_2 \qquad (6)$$

where:

$$A_1=S\left[jZ_{1M}-X_2\left(1+\frac{Z_{1M}}{Z_M}\right)\right] \qquad (7)$$

$$B_1=-\left[aZ_2+(Z_{1S}+Z_C)\left(\frac{1}{a}+a\frac{Z_2}{Z_S}\right)\right] \qquad (8)$$

$$C_1=V\left[S\left(j-\frac{X_2}{Z_M}\right)-\left(\frac{1}{a}+a\frac{Z_2}{Z_S}\right)\right] \qquad (9)$$

$$A_2=\left[Z_{1M}\left(1+\frac{Z_2}{Z_M}\right)+Z_2\right] \qquad (10)$$

$$B_2=S\left[-aX_2+(Z_{1S}+Z_C)\left(j/a-a\frac{X_2}{Z_s}\right)\right] \qquad (11)$$

$$C_2=V\left[\left(1+\frac{Z_2}{Z_M}\right)+S\left(j/a-a\frac{X^2}{Z_S}\right)\right] \qquad (12)$$

Then by determinants:

$$I_M=\frac{C_1B_2-C_2B_1}{A_1B_2-A_2B_1} \qquad (13)$$

$$I_S=\frac{A_1C_2-A_2C_1}{A_1B_2-A_2B_1} \qquad (14)$$

From (1) and (2),

$$I_y=I_M\left(1+\frac{Z_{1M}}{Z_M}\right)-\frac{V}{Z_M} \qquad (15)$$

$$I_x=I_S\left(\frac{Z_S+Z_{1S}+Z_C}{Z_S}\right)-\frac{V}{Z_S} \qquad (16)$$

For rotor-locked conditions, (13) and (14), reduce to

$$I_M=\frac{V}{Z_{IM}+\left(\dfrac{Z_2}{1+\dfrac{Z_2}{Z_M}}\right)} \qquad (17)$$

$$I_S=\frac{V}{(Z_{IS}+Z_C)+\dfrac{aZ_2}{\dfrac{1}{a}+a\dfrac{Z_2}{Z_S}}} \qquad (18)$$

The counter electromotive forces in the separate windings are:

$$E_M=V-I_MZ_{IM} \qquad (19)$$

$$E_S=V-I_S(Z_{IS}+Z_C) \qquad (20)$$

The rotor input, or the power transferred across the gap, is the sum:

$$E_MI_y\cos(E_M,I_y)+E_SI_x\cos(E_S,I_x) \qquad (21)$$

The power converted to mechanical form:

$$\text{Power across gap by }(21)-(I_y^2+a^2I_x^2)r_2=ST \qquad (22)$$

Net output = power converted to mechanical form $-(F\,\&\,W)$ (23)

The torque in synchronous watts, (T) is the sum:

$$aE_MI_x\sin(E_M,I_x)+\frac{E_S}{a}I_y\sin(E_S,I_y) \qquad (24)$$

The stator input is the sum:

$$VI_M\cos\theta_M+VI_S\cos\theta_S \qquad (25)$$

The stator losses:

$I_M^2r_{1M}$ = copper loss in the main winding (26)

$I_S^2(r_{1S}+r_C)$ = copper loss in start winding circuit (27)

$$\frac{E^2M}{r_0}+\frac{E_S^2}{r_{0S}}=\text{iron losses} \qquad (28)$$

The rotor losses:

$I_y^2r_2$ = copper loss in the y-axis (29)

$a^2I_x^2r_2$ = copper loss in the x-axis (30)

Some attention should be given to the matter of iron losses. In the double-field theory of Morrill, the iron losses are neg-

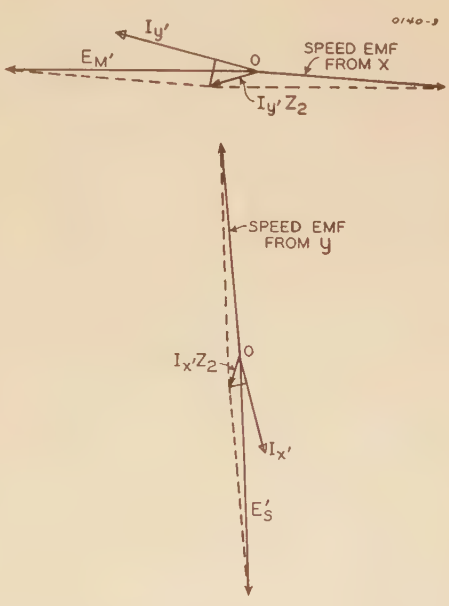


Figure 3. The rotor current and voltage vectors

lected in the equations, but good results are claimed for a correction based on consideration of these losses as external to the motor. In the use of the revolving-field analyses it has been the experience of the present writers that a lack of agreement may result between calculated and test values, particularly in the start winding under running conditions. This may be due to saturation, harmonics, or both, corrections for which are not readily introduced in the equations.

If desired, the iron losses can be considered in the symmetrical-component method of Lyon and Kingsley,[9] or in the method of Punga[10] which rests on the polyphase motor. The work of Y. Hasumi[11] on the symmetrical-component basis indicates a very simple method of introducing the iron losses in Morrill's equations by using for forward and backward impedance, respectively, the terms:

$$Z_f = \frac{1}{\frac{1}{r_0} + \frac{1}{jX_m} + \frac{1}{r_{2/s} + jX_2}} = R_f + jX_f \qquad (31)$$

$$Z_b = \frac{1}{\frac{1}{r_0} + \frac{1}{jX_m} + \frac{1}{r_{2/2-s} + jX_2}} = R_b + jX_b \qquad (32)$$

In any case the labor involved is considerable, the efforts to reduce it, such as by the method of Krondl,[12] or by tabulated form sheets and curves, have met with partial success.

In the method used here with the cross-field theory the magnetizing reactance of the main axis is jX_M. The addition of a core-loss resistance in that axis, transferred to an equivalent series value, gives an impedance of the magnetizing branch as

$$Z_M = \frac{1}{\frac{1}{r_0} + \frac{1}{jX_M}} \qquad (33)$$

If widely different saturation and core losses occur in the cross-axis, the values should be modified but the magnetizing impedances in the two axes take the same form; thus:

$$Z_S = \frac{1}{\frac{1}{r_{0s}} + \frac{1}{jX_s}} \qquad (34)$$

Neglecting the iron losses, with the idea of considering them later as external to the motor, results in the reduction of Z_M and Z_S to jX_M and jX_S, respectively.

Symbols

V = applied volts. Used as reference vector

E_M = the counter electromotive force in the main axis

$Z_{1M} = r_{1M} + jX_{1M}$ = the impedance (local) of the main stator winding

Z_2 = the rotor impedance in main winding terms (local) $= r_2 + jX_2$

E_S = the counter electromotive force of the start or capacitor winding

$Z_{1S} = r_{1S} + jX_{1S}$ = the local impedance of the stator start winding

$Z_C = r_C - jX_C$ = capacitor impedance

I_M = the stator current, main axis

I_S = the stator current, start axis

$I_{\phi M}$ = the magnetizing current, main axis

$I_{\phi S}$ = the magnetizing current, start axis

I_y = the stator component of the rotor current, main axis

I_x = the stator component of the rotor current, start axis

Z_S = the magnetizing impedance in the S-axis

Z_M = the magnetizing impedance in the M-axis

$$Z_S = \frac{1}{\frac{1}{r_{0S}} + \frac{1}{jX_S}}$$

$$Z_M = \frac{1}{\frac{1}{r_0} + \frac{1}{jX_M}}$$

$$a = \frac{\text{Effective start winding turns}}{\text{Effective main winding turns}}$$

$$S = \frac{\text{Actual rpm}}{\text{Synchronous rpm}}$$

s = slip

Table I. Motor Running With a Slip of Four Per Cent

Method	I_M	I_S	Input and Iron	$I_M^2 r_{1M}$	$I_S^2 \cdot (r_C + r_{1S})$	Rotor Copper	Friction and Windage	Net Output
Morrill	$2.47\angle 59°3'$	$0.948\angle 38°46'$	221+24	12.3	14.5	11.4	13	177
Lyon & Kingsley	$2.57\angle 55°48'$	$0.935\angle 38°40'$	239	13.3	14.1	11.8	13	165
Punga	$2.57\angle 56°30'$	$0.948\angle 40°50'$	234	13.3	14.5	10.9	13	162
Cross-field	$2.64\angle 58°36'$	$0.954\angle 39°0'$	233+24	14.1	14.7	13.2	13	177 to 179.8

Vector Diagrams

One advantage of this analysis rests in the graphical picture which can readily be obtained for the physical relationships by vector diagrams. Figure 1 indicates the stator voltage components, as well as the usual positions of the stator currents.

In figure 2 are shown the current components and the flux vectors. The vectors $I_{\phi S}$ and $I_{\phi M}$ indicate magnetizing currents for the respective axis.

Rotor vector relationships are shown in figure 3. Rotor currents and voltages are reversed with respect to their respective positions when transferred to the stator and are indicated by prime terms. Experience indicates that I_X' may fall in either the third or fourth quadrants. The vectors shown here represent the solution of equations 3 and 4.

Summary and Comparative Results

A number of examples have been calculated by this cross-field analysis, one of which is shown in the appendix. The final data are tabulated in tables I and II along with results on the same motor as obtained through other analyses. The method throws light on the phenomena from another point of view and a favorable degree of accuracy is indicated with a competitive ease (or difficulty) of application.

To the engineer who has become thoroughly familiar with the calculation of capacitor-motor performance by the double-field theory, using convenient tabulations of equations, the use of this cross-field analysis will probably appear long and complex. However, considerable experience in handling these equations has led the writers to the belief that for time involved and complexity of calculation there is little to choose between the double-revolving and the cross-field theories. Advantages, then, for this analysis can be found chiefly in the fact that different saturation effects in the two axes can be considered more easily and that the equations result in vector diagrams which are significant in showing the effect of various design changes. This is particularly true in dealing with the conditions necessary for balanced "two-phase" operation, although detailed derivations for this application will not be carried out here. With this analysis a revolving field will exist when:

$$jI_y' = I_X' \qquad (35)$$

$$jE_M' = \frac{E_S'}{a} \qquad (36)$$

Either of these relations is sufficient as indicating that the fluxes are equal and in quadrature. With the rotor currents in terms of the main winding (35) becomes:

Table II. Starting Conditions

Method	I_M	I_S	Input and Iron	$I_M^2 r_{1M}$	$I_s^2 \cdot (r_C + r_{1S})$	Starting Torque (Synchronous Watts)
Morrill	$14.2\diagdown 40^\circ 50'$	$6.30\angle 27^\circ 55'$	1,796+24	406	401	755
Lyon & Kingsley	$14.0\diagdown 40^\circ 50'$	$6.20\angle 27^\circ 50'$	1,750	398	390	728
Punga	$14.2\diagdown 40^\circ 45'$	$6.28\angle 27^\circ 40'$	1,790	406	400	708
Cross-field	$14.2\diagdown 40^\circ 0'$	$6.25\angle 27^\circ 50'$	1,800+24	408	396	759

$$jI_y = aI_X \qquad (37)$$

Also, in main winding terms:

$$jI_M = aI_S \qquad (38)$$

When this is used the total revolving magnetomotive forces are indicated as being equal and in quadrature

The problem of obtaining a true revolving field has also been discussed by Specht[13] and Trickey[14] in this country. Some interesting relationships developed by Punga,[10] Krondl,[12] and Wolf[15] do not seem to be generally known. For example when stator main and start windings have equal copper and result in equal saturation, a true revolving field is obtained at some prescribed slip s when

$a = \tan\phi$ (Punga and Krondl)

and

$X_C = (a^2 + ja)Z$ (Punga)

wherein:

ϕ = the power factor angle of a two-phase motor with both phases like the main and operating at a slip s

Z = the machine impedance of phase M at a prescribed slip s, for a two-phase motor

Z_0 = the machine impedance similar to Z above, but at a slip of $2-s$

All of these quantities can be obtained from the equivalent network, other equations, or the circle diagram of a two-phase motor.

Trickey's formulas for balanced condition are somewhat longer than those pertaining to the analyses quoted above although they have greater generality. Punga indicates an interesting relationship, in that under the assumptions of equal copper and saturation, I_M becomes zero when for some given value of slip, the capacitor impedance is fixed thus:

$$Z_C = -\frac{Z_0(a^2 - ja) + Z(a^2 + ja)}{2}$$

No one familiar with the process of designing capacitor motors can be thoroughly satisfied with the present analytical or design tools available to the designer. No convenient expression has been derived for the speed-torque curve nor for the maximum torque that can be developed. The lack of such equations as well as simplified forms of many other relationships, has proved a serious handicap. In the long run such developments result only from the examination of all available theories and viewpoints. It is the hope of the present writers that the cross-field analysis may be a step forward in aiding more useful analyses to be developed.

Appendix I

To illustrate the application of the cross-field theory an example will be worked out using the same motor for which constants are given in Morrill's[4] paper. The values for this four-pole one-fourth horsepower 110-volt motor are:

$r_{1M} = 2.02$
$r_{1S} = 5.12 \times 1.18^2 = 7.13$
$r_2 = 4.12$
$r_C = 9.00$
$X_{1M} = 2.79$
$X_{1S} = 2.31 \times 1.18^2 = 3.22$
$X_2 = 2.12$
$X_C(\text{running}) = -172.0$
$a = 1.18$
$X_M = 66.8$
$X_S = 92.9$

Friction and windage = 13 watts
Iron losses = 24 watts

On any given motor these constants can be obtained by the usual test methods applicable to the ordinary single-phase motor, using each winding independently. Their calculation from a design sheet involves the usual processes pertaining to the single-phase motor found in standard works on design. It is necessary to recall that the machine acts as a transformer in each of its two axes and that consideration must be given (in calculations of rotor constants) to the winding to which these constants are referred. Furthermore, as noted in this example, magnetizing reactance, and rotor resistance and leakage reactance have twice the values by the cross-field theory that they would display for the double revolving field method.

In this example, the use of an equivalent iron loss resistance will be neglected and hence Z_M and Z_S reduce to the respective values of jX_M and jX_S.

Performance will be calculated at a slip of 0.04.

From:

(7) $A_1 = -4.80 + j2.00$
(8) $-B_1 = 10.14 - j145.9$
(10) $A_2 = 6.367 + j4.876$
(11) $B_2 = 139.1 + j13.55$
(9) $C_1 = -96.2 + j114.7$
(12) $C_2 = 113.5 + j85.6$
(13) $I_M = 2.64\diagdown 58^\circ 36'$
(14) $I_S = 0.954\angle 39^\circ 0'$
(15) $I_y = 1.55\diagdown 28^\circ 30'$
(16) $I_x = 0.757\angle 131^\circ 25'$

The magnetizing current ($I\phi_M$) in the main axis $= I_M - I_y$
$= 0.015 - j1.51$

In the cross-axis ($I\phi_S$): $I_S - I_x = 1.241 + j0.034$

(19) $E_M = 102.67\angle 0^\circ 19'$
(20) $E_S = 113.5\angle 91^\circ 16'$

The rotor input:

$E_M I_y \cos(E_M, I_y) = 102.67 \times 1.55 \times \cos(28^\circ 30' + 0^\circ 19')$
$= 140$ watts from the main axis

$E_S I_X \cos(E_S, I_x) = 113.5 \times 0.757 \times \cos(131^\circ\ 25' - 91^\circ 16')$
$= 66$ watts from the cross axis

Total input to rotor = 206 watts

The rotor losses:

$I_y^2 r_2 = 1.55^2 \times 4.12$ or 9.9 watts
$a^2 I_x^2 r_2 = 1.18^2 \times 0.757^2 \times 4.12$ or 3.3 watts
Friction and windage = 13.0 watts
Total rotor losses......26.2
Net output = 206 − 26.2 or 179.8 watts

The stator input:

$VI_M \cos\theta_M = 110 \times 2.64 \times \cos 58^\circ 36'$
$= 151$ watts
$VI_S \cos\theta_S = 110 \times 0.954 \times \cos 39^\circ$
$= 82$ watts
Total input = 233 watts

The stator losses:

$I_M^2 r_{1M} = 2.64^2 \times 2.02$ or 14.1 watts
$I_S^2(r_{1S} + r_C) = 0.954^2(7.13 + 9)$ or 14.7 watts
Total stator losses = 28.8

Note that iron losses have been neglected throughout rather than calculated as in equation 28 and considered with the stator losses.

Output from input − losses = 233 − 28.8 − 26.2 or 178 watts.

This checks fairly well with rotor output of 179.8 watts, as calculated.

The torque from (24),

$1.18 \times 102.67 \times 0.757 \times \sin 131^\circ 6' = 69.0$ synchronous watts

$\frac{113.5}{1.18} \times 1.55 \times \sin 119^\circ 46' = 129.0$ synchronous watts

Total torque, in synchronous watts = 198.0

$$\text{Ounce feet} = \frac{112.7 \text{ synchronous watts}}{\text{synchronous rpm}}$$

The power converted to mechanical form $= ST$
$= 0.96 \times 198$ or 190 watts

The output = 190 − 13 (friction and windage) = 177 watts

Some Insulator Designs Require Special Features to Insure Radio Quietness

CHARLES J. MILLER, JR.
ASSOCIATE AIEE

Synopsis: The suggested requirements for radio-free pin-type, switch and bus, and suspension insulators, if acceptable, indicate and justify from a factory testing and production viewpoint, the following conclusions as regards existing standard designs:

1. For distribution voltages up to 4,400 or even 5,500 volts, the small one-piece pin-type insulators used require no "radio-proofing", even on solidly grounded pins.

2. If there is 6 to 12 inches of crossarm in series with small one-piece pin-type insulators on low-voltage distribution lines up to 13 kv, no "radio-proofing" is needed on the insulators.

3. Standard untreated pin-type insulators used on 17 to 69-kv distribution and transmission lines have radio noise-influence voltages in the order of several thousand microvolts at a test potential about ten per cent above the usual line-to-ground voltages. "Radio-proofed" pin-type insulators, readily meeting reasonable requirements for freedom from radio interference, are available for use on lines in this voltage range.

4. Standard cemented pin-and-cap switch and bus insulators up to the 69-kv rating, with the exception of the 66-*S*-class, readily meet the suggested requirements for freedom from radio interference without any special "radio-proofing" treatment; they are inherently quiet.

5. Standard switch and bus insulators for the 66-*S*-class and the 115-kv and higher-voltage classes may require "radio-proofing" or other precautions to meet the suggested abnormally low requirements. These insulators with slight changes can be made to meet these requirements readily.

6. Regular cemented pin-and-cap suspension insulators of modern manufacture readily meet the suggested requirements for freedom from radio interference without any form of "radio-proofing"; they are inherently quiet.

RADIO interference originating on electrical power lines and substations has been studied extensively during the past 10 or 15 years by both the utility engineers and the manufacturers of equipment and materials used in construction. While it is the responsibility of the former to utilize properly the materials available for building their lines, they cannot construct a line or substation which is better than any of its component parts. Therefore, at least part of the responsibility for radio-free power lines and substations is passed on to the manufacturers of materials used in their construction.

Primarily, a power line or substation consists of several conductors which are mechanically held in place and electrically isolated from ground and from each other by means of insulators. The several conductors have a potential with respect to each other and also with respect to ground. One end of an insulator is at the potential of the attached conductor while the other end of the insulator may be at ground potential, or it may have supplementary insulation to ground such as a wood crossarm or a section of a wood pole.

In a three-phase system with a grounded neutral the maximum voltage which can appear across an insulator is the line-to-line voltage divided by 1.732. With wood in series with an insulator to ground, the voltage across the insulator itself may be somewhat less than indicated above. In a three-phase system with an ungrounded neutral an accidental grounding of one of the conductors may place the full line-to-line voltage across the insulators of the other two phases. But this is an abnormal condition which would occur only rarely and then would undoubtedly be corrected as soon as possible. Therefore, the greatest voltage which would normally appear across an insulator in a three-phase system is 0.577 of the line-to-line voltage. For convenience, this voltage is often called the "operating voltage" of the insulator.

Insulators as a Source of Radio Interference

If a power line or substation is to be free from radio interference, it is essential

Paper **40-144**, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE Middle Eastern District meeting, Cincinnati, Ohio, October 9–11, 1940. Manuscript submitted August 9, 1940; made available for preprinting September 18, 1940.

CHARLES J. MILLER, JR., is electrical engineer. Ohio Brass Company, Mansfield, Ohio.

Thus by three different approaches outputs of 179.8, 178.9, and 177 watts are obtained. The discrepancies are largely due to slide rule error as a ten-inch slide rule was used throughout.

With a starting capacitor of 3 ohms resistance and 14.5 ohms reactance, the starting conditions can be calculated as shown below:

From (17) $I_M = 14.2\diagdown\overline{40°0'}$

(18) $I_S = 6.25\diagup\underline{27°50'}$

A convenient method of determining I_y and I_x is to substitute the numerical values of I_M and I_S in equations 1 and 2 respectively.

Then,

$$I_x = \frac{j78.6\ I_S}{4.86 + j81.1} \quad \text{or } 6.06\diagup\underline{31°20'}$$

This is in terms of S winding; in terms of M:

$I_x = 1.18 \times 6.06$ or 7.15 amperes

Similarly:

$$I_y = \frac{j66.8 I_M}{4.12 + j68.92} \text{ or } 13.8\diagdown\overline{36°34'} \text{ amperes}$$

The counter electromotive force

$$E_M = jX_M(I_M - I_y)$$
$$= 63.6\diagdown\overline{10°47'}$$
$$E_S = jX_S(I_S - I_x)$$
$$= 38.8\diagup\underline{57°0'}$$

The starting torque:

$$aE_M I_x \sin (E_M, I_x) = 1.18 \times 63.6 \times 6.06 \sin 42°7' \text{ or } 306$$

$$\frac{E_S}{a} I_y \sin (E_S, I_y) = \frac{38.8}{1.18}\ 13.8 \sin 93°34' \text{ or } 453$$

In synchronous watts: 306+453 or 759

References

1. DIE INDUKTIONSMASCHINE ALS PHASENUMFORMER, **Brüderlin.** *Arbeiten elektrotechnischen Inst. Karlsruhe*, volume 4, 1920.

2. DIE ORTSKURVEN DER GRAPHISCHEN WECHSELSTRONTECHNIK (a book), **O. Bloch.** Rascher and Company, Zürich.

3. UEBER EINEN EINPHASEN-INDUKTIONS-MOTOR, **J. Biermanns.** *Arch. für Elek.*, 1926, page 519.

4. THE REVOLVING FIELD THEORY OF THE CAPACITOR MOTOR, **W. J. Morrill.** AIEE TRANSACTIONS, April 1929.

5. DER EINPHASIGE INDUKTIONSMOTOR IN GRAPHISCHE-ANALYTISCHER DARSTELLUNG, **J. K. Sumec.** *Zeitschrift für Elektrotechnik*, September 6, 1903.

6. DIE WECHSELSTROMTECHNIK (a book), **E. Arnold.** Volume 5, part 2, Julius Springer, Berlin.

7. THEORY AND CALCULATION OF ELECTRICAL APPARATUS (a book), **C. P. Steinmetz.** McGraw-Hill Book Company.

8. THE CROSS-FIELD THEORY OF ALTERNATING CURRENT MACHINES, **H. R. West.** AIEE TRANSACTIONS, volume 45, 1926.

9. ANALYSIS OF UNSYMMETRICAL MACHINES, **W. V. Lyon and Charles Kingsley, Jr.** ELECTRICAL ENGINEERING (AIEE TRANSACTIONS), May 1936.

10. DAS STROMVEKTORDIAGRAM DES EINPHASENMOTORS MIT KAPAZITÄT IN DER HILFSPHASE, **F. Punga.** *Elektrotechniche Zeitschrift*, March 30 and April 13, 1933.

GRAPHISCHE BEHANDLUNG DES EINPHASEN-INDUKTIONS-MOTOR MIT KAPAZITÄT UND HILFSPHASE, **F. Punga.** *Arch. für Elek.*, volume 18, 1927, page 267.

11. THEORY OF THE CAPACITOR MOTOR, **Y. Hasumi.** JIEE (Japan), 1934.

12. BERECHNUNG VON EINPHASEN-KONDENSATOR-MOTOREN, **M. Krondl.** Zürich-Oerlikon, Bulletin number 6, XXV Year, 1934, pages 143–7.

13. THE FUNDAMENTAL THEORY OF THE CAPACITOR MOTOR, **H. C. Specht.** AIEE TRANSACTIONS, April 1929.

14. DESIGN OF CAPACITOR MOTORS FOR BALANCED OPERATION, **P. H. Trickey.** AIEE TRANSACTIONS, September 1932.

15. DER EINPHASEN-INDUKTIONSMOTOR MIT KONDAENSTOREN IN DER HILFSPHASE, **Hans Wolf.** *Arch. für Elek.*, volume 23, 1930, pages 459–84.

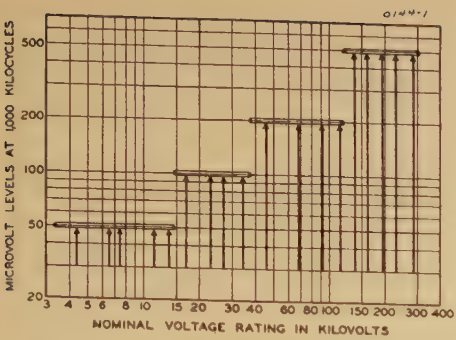


Figure 1. Proposed maximum radio noise-influence voltage levels for "radio-free" insulators

that the insulators used in its construction will not cause disturbance under normal operating conditions. On the other hand, it must not be assumed that the use of "radio-free" insulators will prevent radio disturbance from being generated by the other components used in construction.

The realization that certain types of insulators have been responsible for part of the radio noise emanating from power lines and substations has been the incentive for progressive insulator manufacturers to develop insulators which cannot cause radio disturbances when properly placed in service. Since the high-voltage pin-type insulator was the principal offender, the pioneer investigations were made on this type. (See "Behavior of High-Voltage Insulators on Radio Test," by Charles J. Miller, Jr., in *Electrical World*, March 25, 1939, pages 45–8.)

Fundamentally, the radio interference originating from insulators is caused by an electrically overstressed condition of the air adjacent to certain regions of the insulator. Fortunately, overstressed air, besides giving rise to radio interference, makes its presence known by a visual phenomenon commonly called corona, or corona discharge. This visual corona enabled the pioneer radio-interference investigators to locate the regions of electrical overstress on the pin-type insulator. It was found that these principal regions were at the conductor and tie wire and in the pin hole where thin layers of air were being subjected to intense electric fields. The obvious solution to this problem was to eliminate the air from these critical regions or to alter the design of the insulator in such a way that the intense dielectric field of the insulator between the pin and the conductor and tie wire existed wholly within the dielectric medium of the insulator and not across these layers of air.

Methods of Radio-Proofing Insulators

A conduction paint was developed which could be brushed around the head of the pin-type insulator and in the pin hole. This conduction paint altered the electric field in the critical regions and reduced the noise level of the insulator by many times. However, this paint was too temporary a remedy to be a final solution of the problem. Progressive manufacturers were not satisfied with a temporary remedy and continued the search for a permanent treatment which would last the life of the insulator.

The pin-hole problem was readily solved by cementing a zinc thimble or metal insert into the pin hole. The cement, being a semiconducting medium readily transfers the flux lines from the inner surface of the porcelain to the metal thimble.

The top of the insulator presented a bigger problem and numerous devices were used to attain the desired end. Certain designs were brought out with cemented metal hardware on top of the insulator. Some of these designs have excellent radio properties. Other designs have metallized coatings bonded to the critical area of the insulator by various means. The most recent designs utilize conducting glazes in the critical regions. This type of treatment is being very widely adopted on pin-type insulators because of its satisfactory characteristics and ease of application.

The EEI-NEMA-RMA Measuring Circuit

Along with the advancement of the art of "radio-proofing" insulators came the development of a factory means of measuring the radio-interference properties of equipment and insulators. In the early days of the art, each manufacturer devised his own method of testing and, consequently, when the time came to compare results, it was found that there was no common yardstick for measuring radio interference.

In the meantime the Edison Electric Institute, National Electric Manufacturers Association, and Radio Manufacturers Association were faced with the problem of measuring all sorts of radio interference from all types of equipment. To study the problem in general, the three organizations appointed a committee which came to be known as the "Joint Co-ordination Committee on Radio Reception of EEI, NEMA, and RMA." This committee devised a method of measuring radio noise and established

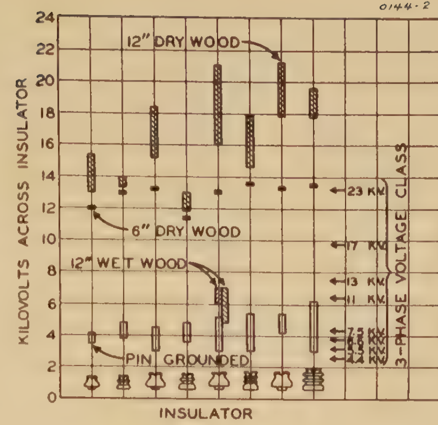


Figure 2. Kilovolts necessary to produce a radio noise-influence voltage of 50 microvolts on small one-piece pin-type insulators with the pin grounded and with wood in series with the insulator

various standards for these measurements. A pamphlet entitled "Methods of Measuring Radio Noise" was published in December 1935 by the joint committee. The latest publication by this committee (EEI Publication No. *G*9—NEMA Publication No. 107—RMA Engineering Bulletin No. 32) is entitled "Methods of Measuring Radio Noise, 1940" and was published in February 1940.

The joint committee devised a circuit to be used for high-voltage devices. This circuit was adopted by leading insulator manufacturers in 1937 and has been the recognized method of test since. (See "Establishes Method of Measuring Radio Interference," by Charles J. Miller, Jr.,

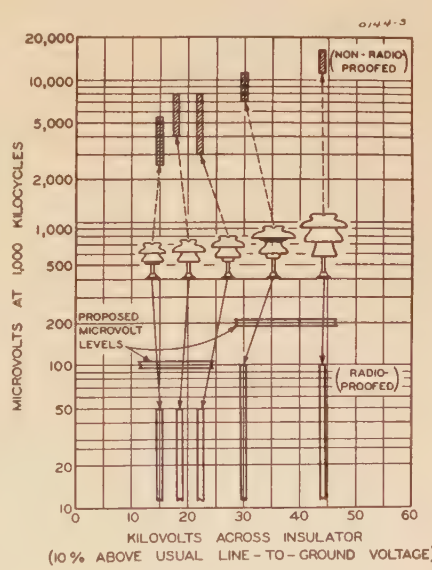


Figure 3. Radio noise-influence voltages from regular pin-type insulators at a test voltage about ten per cent above the usual line-to-ground voltage

in *Electrical World*, March 11, 1939, pages 48–50.)

The insulator to be tested is placed in the circuit and a 60-cycle potential is applied across it. The radio noise voltage generated by the insulator is measured with the radio noise meter and is expressed in "microvolts." The term "radio noise-influence voltage" has been adopted as the official name to be applied to the voltage reading obtained from the radio noise meter when the specimen is tested in the EEI-NEMA-RMA recommended circuit.

Requirements for Radio-Free Insulators

To be free of radio interference, insulators must meet certain requirements when tested in the EEI-NEMA-RMA circuit. Based on field experience and known characteristics of available "radio-free" insulators, the majority of manufacturers of high-voltage insulators have suggested radio noise-influence voltage levels which will insure freedom from interference of various classes of insulators under service conditions.

Radio interference originating on a power line may be transferred to a nearby antenna by direct coupling between the power line and antenna, or it may be carried an appreciable distance along a low-voltage distribution line and then be transferred to a receiving antenna. (See "Sources of Radio Interference and How to Eliminate Them" by Paul M. Ross, in *Electric Light and Power*, September 1939, pages 38–9.) In the latter case, coupling must exist between the power line and the low-voltage distribution line and also between the distribution line and the antenna.

The farther the distribution line or the antenna from the power line, the smaller is the transfer of radio interference. In general, the higher the voltage of a power line, the greater is its distance from low-voltage distribution lines and antennas. Accordingly, it seems quite reasonable to select a maximum permissible microvolt radio noise level in keeping with the voltage of the line.

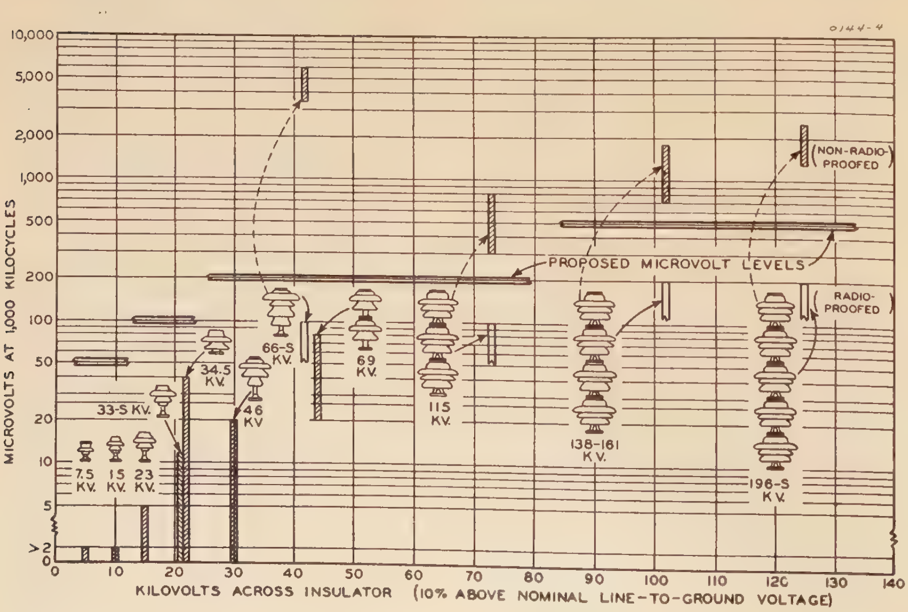
Low-voltage distribution lines up to the 13-kv class cover widespread areas and are more or less closely coupled to distribution networks supplying individual homes. It is felt that a maximum radio noise-influence voltage of about 50 microvolts for insulators used on these lines will insure freedom from radio noise provided the radio noise-influence voltages of all other components of the line are also below equally satisfactory levels. Obviously, disturbance on a power line arising from sources other than insulators cannot be blamed on the insulators, nor can "radio-free" insulators suppress radio interference arising from these other sources.

Power lines in the 17 to 34.5-kv classes are, in general, not as closely coupled to the distribution networks and, therefore, a maximum radio noise-influence voltage of about 100 microvolts seems to be a reasonable level. In the range from 46 to 115-kv classes, a level of 200 microvolts should provide adequate protection from radio interference. Transmission lines in the 138 to 287-kv classes seldom parallel lower-voltage lines for any appreciable distance and are generally more or less remote from areas of population. Accordingly, a maximum radio noise-influence voltage of about 500 microvolts seems to be a reasonable figure. Figure 1 illustrates graphically these proposed maximum radio noise-influence voltage levels for radio-free insulators for the various voltage classes.

The radio noise-influence voltage of an insulator is dependent upon the voltage across it. In actual service an insulator is subjected to the line-to-ground or operating voltage. Every transmission line has a "nominal" voltage rating which may be slightly different than the actual voltage. Furthermore, the actual voltage on a transmission line may be higher at the sending end than at the receiving end. To compensate for possible voltage variations from the nominal value, it seems quite logical to subject the insulator to a test voltage about 10 per cent higher than the nominal line-to-ground voltage when testing it in the EEI-NEMA-RMA circuit.

With a standard method for measuring the radio noise-influence voltage produced by an insulator and with a set of requirements which must be fulfilled by a "radio-free" insulator, the insulator manufacturer has at his disposal a radio-interference yardstick with which he can judge the merits of the insulators he manufactures.

Figure 4. Radio noise-influence voltages from regular pin-and-cap switch and bus insulators at a test voltage about ten per cent above the nominal line-to-ground voltage



Radio Noise-Influence Voltages of Various Types of Insulators

Having a definite yardstick for measuring the radio interference properties of insulators, a survey of available insulators of all types provides an interesting study. Briefly, such a study leads to the conclusion that certain types of insulators which have been manufactured for years require no special "radio-proofing" to meet the suggested requirements for freedom from radio interference; they are inherently quiet.

Conducting glazes provide effective "radio-proofing" on pin-type insulators. However, it does not necessarily follow that conducting glazes are required on all designs and classes or that they provide the only effective means of "radio-proofing" an insulator. For example, pin-type insulators which are "radio-proofed" with metallized coatings or cemented hardware are available.

Small One-Piece Pin-type Insulators

Small one-piece pin-type insulators are commonly used on low-voltage distribu-

tion circuits. In many cases these insulators are mounted on wood crossarms. This provides a section of wood in series with the insulator to ground or between phases. The voltage divides in proportion to the impedance of the insulator and that of the section of wood, thereby reducing the potential across the insulator from the operating voltage to a lower value. This means that the radio noise-influence voltage to ground from a given insulator will be lower with a section of wood in series with it than with the pin grounded.

A "radio-proof" power line is one which does not interfere with radio reception in nearby homes. It makes no difference how the "radio-proofing" is accomplished so long as the desired results are attained. Small "radio-proofed" pin-type insulators are available for even the lowest-voltage lines. However, before proceeding with the application of "radio-proofed" insulators to these voltage lines, it might be well to stop for a moment and consider the limitations of the old reliable "non-radio-proofed" insulators used for years on the lower-voltage lines.

Figure 2 shows the kilovolts across the insulator necessary to produce a radio noise-influence voltage of 50 microvolts on several different sizes of insulators. Since no two insulators of even the same size give exactly the same results on test, the bands in which all of the test values fall are given. With the pin grounded, the 50-microvolt level falls between 3 and 6 kv for all of the insulators.

Numerous tests were made with 12 inches of dry wood in series with the insulator and a wide range of kilovolt levels was found, ranging from about 12 to 21 kv. A single test was made on each size insulator with 6 inches of dry wood in series with the insulator and the kilovolt levels ranged from 11.5 to 13.5 kv.

Tests were made on one size insulator with 12 inches of very damp wood in series with it. Two samples of wood crossarm were used. These crossarms had been lying outside the laboratory all winter and accordingly were very wet inside, probably much more so than crossarms in service on poles. In spite of this, these crossarms added 2 or 3 kv to the 50-microvolt level voltage.

In any power line, the voltage across the insulator is determined by the operating voltage of the line. In a three-phase system, the voltage across the insulator is generally considered to be the line-to-line voltage divided by the $\sqrt{3}$. It is this voltage which may cause radio interference from the insulator. In figure 2 the line-to-neutral voltage is shown for several

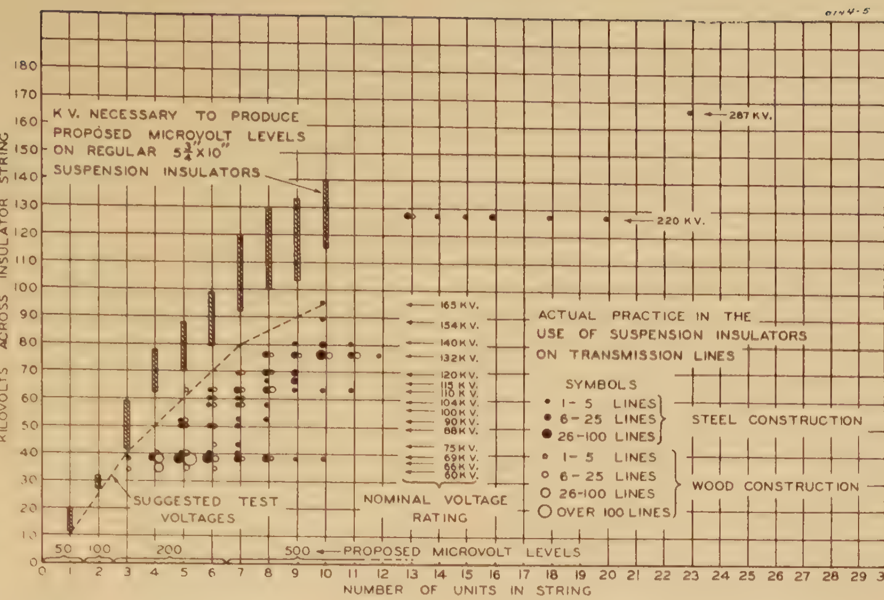


Figure 5. A comparison between the voltages applied to suspension insulator strings in actual practice and voltages necessary to produce the proposed microvolt levels

nominal operating voltages.

Up to and including 4,400-volt lines, not a single insulator would produce as much as 50 microvolts of radio interference even with the pins bonded. Accordingly, the ordinary plain insulator used for years is entirely adequate as regards radio interference and nothing can be gained by using "radio-proofed" insulators on 4,400-volt and lower-voltage power lines.

When there is 6 to 12 inches of dry crossarm in series with the insulator, the 50-microvolt level occurs at such a high voltage that even 13 and 17-kv lines are free from radio interference with the ordinary plain insulator. The actual improvement provided by the wood depends almost entirely upon its moisture content. Real wet wood, a condition existing for infrequent and short periods, may provide only a few kilovolts improvement. In figure 2, wet wood adds from 2 to 4 kv to the 50-microvolt level voltage, but this is enough to assure freedom from radio disturbance on 7.5-kv lines. Crossarms in service exposed to the air would probably never be as wet as the arms tested. Accordingly, it seems reasonable to expect that under average conditions 12 inches of wood in series with the insulator will assure freedom of radio interference from power lines operating at 7.5 kv to ground (13 kv, three phase) and below without the necessity of using "radio-proofed" insulators.

High-Voltage Pin-Type Insulators

The standard pin-type insulators used on 17 to 69-kv distribution lines have radio noise-influence voltages in the order of several thousand microvolts at a test voltage ten per cent above the nominal line-to-ground voltage for which the insulators are commonly used. Figure 3 shows the range of radio noise-influence voltages for five of the popular sizes of pin-type insulators. The proposed microvolt levels are also shown. Obviously, the conventional pin-type insulator cannot qualify as a radio-free pin-type insulator.

Dry wood crossarms in series with these insulators will reduce the noise level a marked degree but in general the reduction is not sufficient to approach the suggested microvolt levels. The only practical permanent solution for the radio-interference problem on the higher-voltage distribution lines is to use "radio-proofed" pin-type insulators which have been manufactured for the purpose. Several types of "radio-proofed" insulators which readily meet the suggested requirements are available. The use of conduction paint or other temporary means of suppression offer an opportunity for satisfactory treatment of existing lines where reinsulation by improved designs cannot be justified.

Switch and Bus Insulators

Generally accepted apparatus voltage ratings have been assigned to the various sizes of switch and bus insulators. The radio noise-influence voltages measured on the various switch and bus insulators at a 60-cycle test voltage about ten per cent above the voltage rating divided by the $\sqrt{3}$ are shown by the bands in figure

4. These are the results of test on the regular cemented pin-and-cap insulators with no "radio-proofing" of any kind. The suggested microvolt levels shown for each of the insulators corresponds with the proposed levels of figure 1.

A substation is generally restricted to a rather small area. Lines leading to and from the substation generally are more or less poorly coupled with it as regards the transfer of radio interference. Accordingly, higher microvolt levels may be permissible within the station than would be permissible on power lines running through residential districts. Other components of a substation which tend toward higher microvolt levels than those suggested for insulators seem to prove that higher levels can and should be permitted in substations. The ease with which switch and bus insulators can be brought to the suggested microvolt levels appears to be the only justification for these ultraconservative values being considered.

A study of figure 4 reveals the important fact that every one of the switch and bus insulators up to and including the 69-kv class, with the exception of the four-part single-unit 66-*S*-kv insulator, has a radio noise-influence voltage which is less than the suggested allowable value for "radio-free" insulators. This means that regular switch and bus insulators up to the 69-kv class, excepting the 66-*S*-class, do not need any special "radio-proofing" treatment to make them quiet; they are inherently so.

The 66-*S*-class insulator definitely requires a "radio-proofing" treatment if the suggested microvolt level is to be met. It has been successfully "radio-proofed" by slight revisions and its radio noise-influence voltage is well below the permissible 200 microvolts at a test voltage 10 per cent above the nominal line-to ground voltage. These revised designs are now the standard products of leading manufacturers.

The stacking insulators used in the 115-kv class and above give radio-influence voltages which exceed the proposed microvolt levels. To meet these suggested levels, slight revisions have been necessary to "radio-proof" these insulators in manufacture.

Suspension Insulators

No definite voltage ratings have been assigned to suspension insulators. In fact a survey of general practice over the entire country reveals an amazing lack of consistency in the application of various suspension string lengths to the various voltage classifications.

The actual practice in the use of suspension insulators on 612 transmission lines throughout the country is shown in figure 5. Of the 612 lines represented, 291 have wood in their construction and 321 are all-steel construction. This information was gathered from published charts and tabulations in technical journals, and, though incomplete, it probably is representative of existing construction.

By considering the shortest insulator string used in each voltage class, which also represents the highest voltage to which a given insulator string may be subjected, it is possible to assign to each string length a maximum microvolt level which is consistent with the proposed levels of figure 1. The proposed microvolt levels assigned to each string length are indicated at the bottom of figure 5.

The kilovolts necessary to produce the proposed microvolt levels for the different string lengths of regular cemented pin-and-cap suspension insulators of modern manufacture are shown by the bands in figure 5. These values are given only for string lengths up to ten units as this was the upper limit of testing equipment available at the time the tests were made. Higher-voltage equipment is now available.

In every case, the minimum kilovolts necessary to produce the proposed microvolt level is well above the highest voltage to which the given string would be subjected in service. In other words, at the highest operating voltage the radio noise-influence voltages from standard unaltered and untreated suspension insulators are less than the proposed microvolt levels for freedom from radio interference. Accordingly, it seems unnecessary to apply special treatment to standard cemented pin-and-cap suspension insulators; they are inherently "radio-free."

It is possible to assign to each string length a 60-cycle test voltage which represents the severest conditions to which the string may be subjected. To be consistent the test voltage assigned to each string length should bear some relation to other string lengths. One such set of assigned values is connected by a curve in figure 5. This curve is more or less the upper envelope of the points representing the suspension insulator applications. There seems to be no reason for placing this curve much higher as this would increase the severity of the radio test on suspension insulators and it would benefit no one.

In spite of the excellent radio characteristics of suspension insulators, conduction glaze has been applied both at the cap and in the pin hole. The cap treatment has increased the visual corona voltages materially. The treatment in the pin-hole area, however, has not proved as successful as at the cap, and in long strings the corona voltage at the pin of the line unit is in general lower than the corona voltage for the corresponding nontreated suspension insulators. The radio noise-influence voltages are generally about the same for the treated and nontreated insulators but there seems to be a tendency for the treated insulators to come lower. The failure of the conduction glaze treatment to provide the improvement found in its other applications is probably due to the configuration of the dielectric field in the pin hole and the inability of the conducting glaze, which must necessarily be applied only to the surface of the porcelain, to alter this field sufficiently to relieve the stress on the adjacent air.

On practically all lines, there are conductor and hardware members operating at high voltages, including clamps or other means for attaching the conductors to the insulators, reinforcing devices such as armor rods, vibration dampers, and similar special items. On a "radio-free" transmission line there must be no disturbances originating from the hardware. When such disturbances occur, they are caused by electrically over-stressed air adjacent to sharp corners or edges of the hardware. Such sources of noise generate a great amount of radio disturbances. Laboratory tests show that when such a disturbance starts, the radio noise-influence voltage jumps abruptly to several hundred microvolts and a small increase in the 60-cycle test voltage is accompanied by a big increase of the radio noise. It is essential in "radio-proofing" a transmission line to be sure that the hardware is adequately designed as well as the insulators.

Performance Calculations on Repulsion Motors

P. H. TRICKEY
MEMBER AIEE

Synopsis: A method of calculating the performance of repulsion motors is developed for the purpose of predetermining the torques and currents, especially for repulsion-start, induction-run motors during the starting period. The method is based on the cross-field theory presented by H. R. West. It is developed along similar lines to the single-phase calculation method presented by C. G. Veinott,[2] and is intended for use in connection with it. The paper presents also the results of investigation showing the effects of varying the several motor constants, and a method of determining the effect of brush resistance.

In a paper presented a number of years ago, H. R. West developed methods of calculating the performance of single-phase induction and repulsion motors, based on the cross-field theory. In 1932, C. G. Veinott further developed the method for single-phase motors, from the point of view of routine calculation, and presented a calculation sheet for this purpose which is now in use in the engineering departments of many motor companies.

It is the purpose of this paper to develop the repulsion-motor method in the same manner, and to offer a calculation sheet of the same general form as that presented by Mr. Veinott. It has been developed particularly for use in conjunction with it in the design of repulsion-start, induction-run motors, but may, of course, be used for ordinary repulsion-run motors.

Repulsion-Motor-Performance Calculations

The circuits of the repulsion motor may be represented by figure 1. The development of the method consists in writing the equations of voltages in the three circuits of the motor in accordance with Kirchhoff's law, and solving these equations for the motor currents and torque. The problem then becomes one of algebraic transformation into a form most suitable for routine solution. This particular derivation has had several important objectives. The first, of course, is speed. Repulsion motors are usually fractional horsepower, and unless the calculation is quickly and easily made, it is more economical to rewind a sample motor once or twice. The second objective is simplicity and clarity. It often

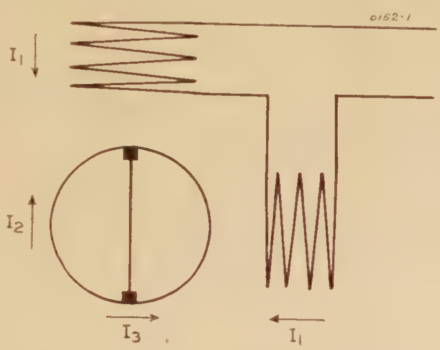


Figure 1. Schematic diagram of the repulsion motor

happens that repulsion-motor designs come at infrequent intervals in the course of designing many other types, usually split-phase or polyphase. It is desirable that the designer be able to proceed immediately into a calculation without any preliminary "brushing up" on the method. Another objective in this case is the possibility of calculating torques and speeds without calculating currents or inputs. This is desirable with repulsion-start, induction-run motors, in obtaining the starting and pull-up torques.

As will be shown later, one of the characteristics of the repulsion motor is that its starting torque is a maximum with no current in the coils short-circuited by the brushes. This would occur with infinite brush resistance. The method has been so arranged that a simple calculation with infinite brush resistance is easily made as a check on the loss of torque due to the short-circuit current.

All of the assumptions and details in the papers of Mr. West and Mr. Veinott hold for this method also. The angle of hysteretic lag between the flux and the magnetomotive force is assumed to be zero. Sinusoidal voltages and currents are assumed. The flux is assumed proportional to the current and magnetomotive force.

The method involves choosing a value of speed, and calculating the performance at that speed. The currents and torques are calculated independently of each other. Although it is possible by this method to obtain a vector solution for the primary current, and from the power component derive the watts input, it was felt as in the case of Mr. Veinott's calculation sheet that a more accurate value would be obtained by adding the losses to the output.

Due to the most frequent use of this method being at the lower speeds and greater currents, it was decided to subtract the iron loss from the output in the same manner as the friction loss.

There is one point in the calculation where it is assumed that the primary and secondary reactances are equal, that is, $x_1=x_2$. This occurs in calculating the constant H_1,

for $x_1 \neq x_2$,

$$H_1=\frac{r_1}{X_0}\left(1+\frac{r_2}{r_3}\right)+\frac{r_2}{X_0}\left(\frac{X_m+x_1}{X_m+x_2}\right)$$

for $x_1=x_2$,

$$H_1=\frac{r_1}{X_0}\left(1+\frac{r_2}{r_3}\right)+\frac{r_2}{X_0}$$

For all ordinary work the second formula is used, but if desired the first one may be followed. Figure 2 shows the small change in performance when the reactances are not equal.

Figure 12 shows the form of the calculation sheet and an illustrative example.

The Effect of Changing the Motor Constants

A number of calculations have been made showing the effect of changing the different constants of the motor. Figure 2 has already been mentioned showing the effect of transferring the reactance from stator to rotor or vice versa. Figure 3 shows the effect of increasing or decreasing the total leakage reactance. The improvement in a motor with increased numbers of slots is largely the result of decreased reactance.

The speed-torque curves of figure 4 show little change with variation of the open-circuit reactance, the greatest change being in the current and power factor. However, it will be noticed that as X_0 decreases, there is finally a reduc-

Paper 40-152, recommended by the AIEE committee on electrical machinery, and presented at the AIEE Middle Eastern District meeting, Cincinnati, Ohio, October 9–11, 1941. Manuscript submitted October 8, 1937; made available for preprinting September 4, 1940.

P. H. Trickey is section head, fractional-horsepower motor design, Diehl Manufacturing Company, Elizabethport, N. J.

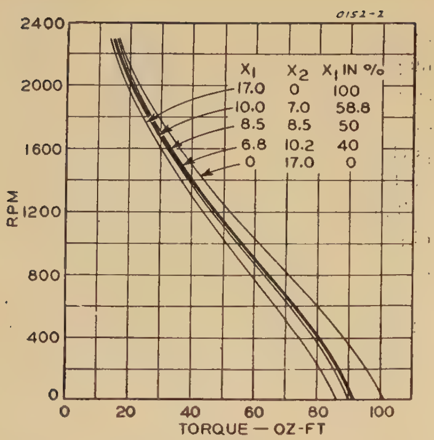


Figure 2. Effect of distribution of leakage reactance between primary and secondary

tion in torque, and it will be found that as the size of the motor decreases or the number of poles becomes greater, this effect will become quite prominent. This is the result of the increased primary impedance drop which reduces the voltage remaining to supply the air-gap flux.

No curves are given for the effect of changing the motor turns, for the result is the same as that obtained by varying the applied voltage, that is, the torques vary as the square of the voltage. Also, any change in the primary resistance has much the same effect, that is, the impedance drop varies and with it the remaining useful voltage.

Figure 5 showing the effect of secondary resistance is somewhat different than for the induction motor, for even at standstill the torque is decreased with increased rotor resistance.

Figure 6 illustrates several interesting points. As will be shown later, r_2 is the resistance of the useful part of the armature, which is made up of a number of coils in series with the brushes. r_3 is the resistance of the short circuits caused by the brushes, and is usually made up of one coil only, in series with two halves of a brush. The several short-circuited coils have the effect of operating in parallel. Figures 6 and 7 show very clearly that the higher r_3, the more desirable the speed-torque characteristics. Whereas, figure 5 shows that r_2 should be decreased for improvement. The problem then is one of increasing r_3 without at the same time increasing r_2. To do this by increasing the resistance of the brush itself is not advantageous beyond a certain point, for although r_3 may be increasing much faster than r_2, a point will be reached when any further increase in r_2 will result in too low pull-up torque. The usual method is to increase the number of coils and commutator bars, which makes the brush resistance a smaller percentage of r_2, and a greater percentage of r_3. It will be noted that r_3 has comparatively little effect on the torque at 75 per cent of synchronous speed, which is the usual operating speed of the short-circuiter, while effecting the starting torque almost directly.

A point of academic interest is obtained with r_3 very low and equal to r_2. Under these conditions, the motor has no starting torque, and operates exactly like a single-phase induction motor. This abnormal condition would be obtained with very wide low-resistance brushes, or with double the regular number of brushes, spaced 45 electrical degrees apart.

It might be noted at this point, that r_3 inherently varies with commutator position as the number of coils short-circuited by the brush changes. For instance, suppose the brush thickness

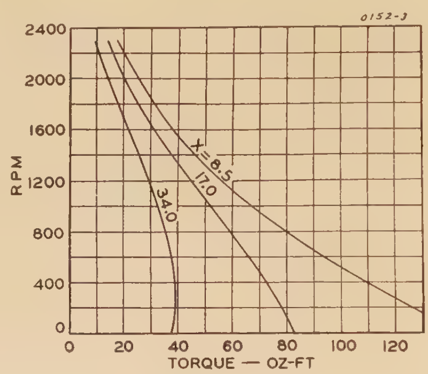


Figure 3. Effect of leakage reactance

equals one commutator bar. In this case, when the brush is exactly over the bar no coils are short-circuited, and r_3 is infinite. When the brush is touching two bars, there is one coil short-circuited under each brush. Thus, r_3 varies from some definite value to infinity, as the rotor passes through one commutator bar pitch. This is the usual case, but supposing the brush is a little wider and can touch three bars at some positions. In this case, r_3 will vary from the worst or lowest value of the narrow brush, to a value which is only half as much.

The most outstanding variable in the repulsion motor is the brush shift. Figures 8 and 9 illustrate the effect on the starting and running torques, respectively. It would, of course, be desirable to operate at the point of maximum starting torque. However, the actual dimensions of the brush shift are not very large, particularly in four-, six-, and eight-pole motors, and to be safe under conditions of manufacturing variations, the brush shift is usually chosen on that side of the peak value corresponding to more shift. This side of the curve is less steep, and if the brush location is not exactly correct, the starting torque will not decrease as much.

Brush Resistance

There is no difficulty in calculating the primary resistance and the reactances of the repulsion motor, but it might be well to discuss the calculation of the secondary resistances r_2 and r_3. One of the difficulties in the design of repulsion motors has been the calculation of that part of r_2 and r_3 caused by the contact resistance of the brushes.

$$r_{2t}=\left[\frac{CKw_m}{2\,tpc\,Kw_{2t}}\right]^2\frac{r_c}{N_c} \qquad (1)$$

$$r_2=\left[\frac{CKw_m}{2\,tpc\,Kw_{22}N_c/a}\right]^2\frac{\dfrac{r_cN_c}{a}+\dfrac{r_b4}{A_b}}{a} \qquad (2)$$

$$r_3=\left[\frac{CKw_m}{2\,tpc\,Kw_m}\right]^2\frac{r_c+\dfrac{r_b4}{A_b}}{a} \qquad (3)$$

where

r_{2t} = rotor resistance referred to the primary when all commutator bars are short-circuited together, and operating as an induction motor
r_2 = rotor resistance as a repulsion motor
r_3 = rotor resistance of the short-circuited coils
r_c = resistance per coil of rotor
r_b = brush contact resistivity, see figure 10
CKw_m = total effective series conductors of primary
tpc = turns per coil in rotor
N_c = number of coils on rotor
a = number of parallel paths in rotor
Kw_{2t} = rotor winding factor (pitch times distribution factor) with commutator short-circuited

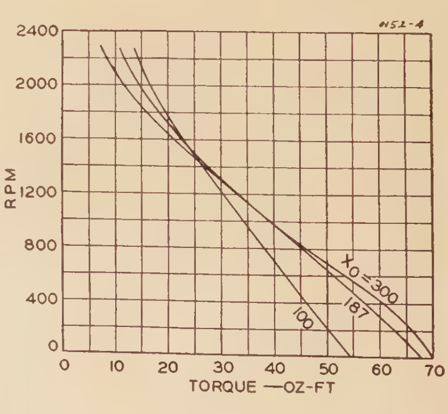


Figure 4. Effect of X_0, the "open-circuit reactance"

Kw_{22} = rotor winding factor operating repulsion
Kw_3 = winding factor of short-circuited coils
A_b = brush area (minus mica area) in square inches

Equation 1 gives the value of rotor resistance r_{2i} to be used for calculation when the motor is operating as an induction motor with all the commutator bars short-circuited. Equation 2 should be used for the rotor resistance r_2 when operating repulsion, and equation 3 should be used for r_3. It can be shown that for uniform coil rotors, Kw_{2i} and Kw_{22} are equal, and it may then be noted that when the brush resistance is equal to zero, r_{2i} equals r_2. It is, therefore, convenient to obtain the value r_2 from the formula given below.

$$\underset{\text{repulsion}}{r_2} = \underset{\text{induction}}{r_{2i}} \frac{R_A+R_B}{R_A} \tag{4}$$

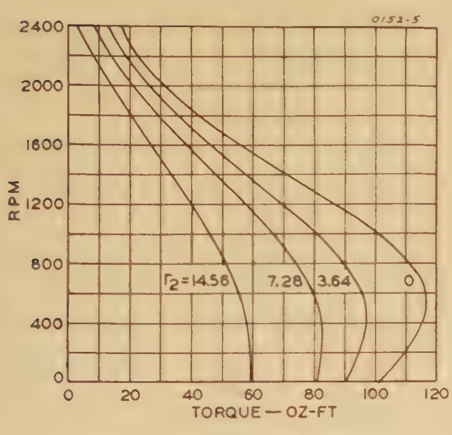


Figure 5. Effect of rotor resistance

where

$$R_A = \frac{r_c N_c}{a} \quad \text{and} \quad R_B = \frac{r_b 4}{A_b}$$

The value for r_3 may be obtained in a similar manner.

$$r_3 = r_{2i}\left[\left(\frac{r_c+R_B}{r_c}\right)\frac{N_c}{a}\,\frac{DF_{2i}}{DF_3}\right] \tag{5}$$

where

DF_{2i} = distribution factor when operating induction (approximately 0.637)
DF_3 = distribution factor for short-circuited coils (usually 1.0)

Figure 10 shows the effect of current density on the brush resistance. To be exact, it would be necessary to use a different value of r_3 corresponding to the current density, for each point of a calculated speed-torque curve. In practice, r_3 is usually high enough so that an average value may be used for the whole curve. It will be found that the brush current densities for most repulsion-start induction-run motors are very high reaching several hundred amperes per square inch during the starting period.

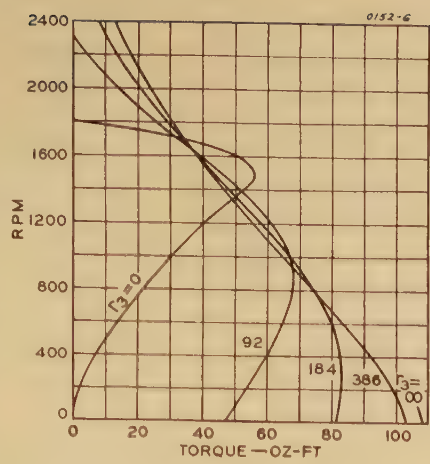


Figure 6. Effect of brush short-circuit resistance

Conclusions and Acknowledgments

The derivation of the equations of the calculation sheet is given in appendix I along with an example illustrating its use. Derivations relating to the motor constants and brush resistances are given in appendix II.

The brush resistance curve of figure 10 is from data furnished by the National Carbon Company.

Partial List of Symbols

(All secondary values are referred to the primary.)

E = applied voltage
I_1 = line or primary current
I_2 = secondary current in main field
I_3 = secondary current in cross field (brush short-circuit current)
r_1 = primary resistance
r_{2i} = rotor resistance as induction motor
r_2 = resistance of main field-rotor circuit
r_3 = resistance of cross-field rotor circuit (brush short-circuit resistance)
X_m = mutual or magnetizing reactance of stator and rotor windings
x_1 = leakage reactance of primary
x_2 = leakage reactance of each rotor circuit
f = frequency
S = speed as a fraction of synchronism
A = angle of brush shift in electrical degrees
Φ_t = flux in transformer axis (main field)
Φ_f = flux in field axis (cross field)

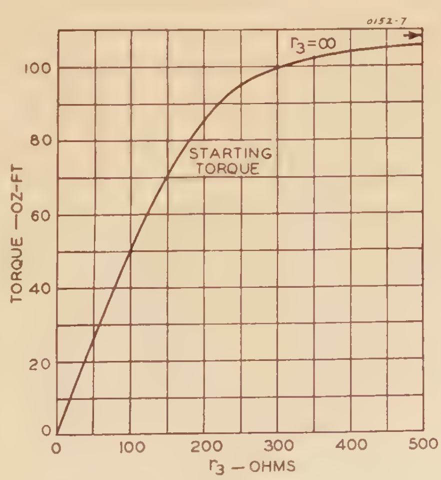


Figure 7. Effect of brush short-circuit resistance on starting torque

Appendix I

Derivation of Repulsion Motor Performance Equations

The circuits of a repulsion motor may be represented schematically by the diagram of figure 1. If A is the angle of brush shift in electrical degrees, the equations for the three circuits may be set up according to Kirchhoff's law. Mr. West[1] writes these equations as given below:

$$E = jX_m(I_1\cos^2 A - I_2\cos A) + jX_m(I_1\sin^2 A - I_3\sin A) + (r_1+jx_1)I_1$$

$$0 = -jX_m(I_1\cos A - I_2) + (r_2+jx_2)I_2 + SX_mI_1\sin A - S(X_m+x_2)I_3$$

$$0 = -jX_m(I_1\sin A - I_3) + (r_3+jx_2)I_3 - SX_m(I_1\cos A - I_2) + Sx_2I_2$$

Solving these equations for the three currents,

$$I_1 = E\times\frac{[r_2r_3-(1-S^2)(X_m+x_2)^2+j(r_2+r_3)(X_m+x_2)]}{U'+jW'}$$

$$I_2 = EX_m\times\frac{[-Sr_3\sin A-(1-S^2)(X_m+x_2)\cos A+jr_3\cos A]}{U'+jW'}$$

$$I_3 = EX_m\times\frac{[Sr_2\cos A-(1-S^2)(X_m+x_2)\sin A+jr_2\sin A]}{U'+jW'}$$

where

$$U' = -r_2X_m^2\cos^2 A - r_3X_m^2\sin^2 A - (r_2+r_3)(x_1+x_2)X_m - (r_2+r_3)x_1x_2 + r_1r_2r_3 - (1-S^2)r_1(X_m+x_2)^2$$

$$W' = r_1(r_2+r_3)(X_m+x_2) + r_2r_3(X_m+x_1) + S(r_3-r_2)X_m^2\sin A\cos A - (1-S^2)\times(X_m+x_2)[X_m(x_1+x_2)+x_1x_2]$$

Torque in synchronous watts =

$$\frac{E^2X_m^2}{U'^2+W'^2}\Big\{(r_3^2-r_2^2)(X_m+x_2)\sin A\cos A + (r_3\sin^2 A+r_2\cos^2 A)[-Sr_2r_3+S(1-S^2)\times(X_m+x_2)^2]\Big\}$$

It is advisable, at this point, to divide the numerator and denominator of the current equations by $(X_m+x_2)^2$ and the torque equation by $(X_m+x_2)^4$.

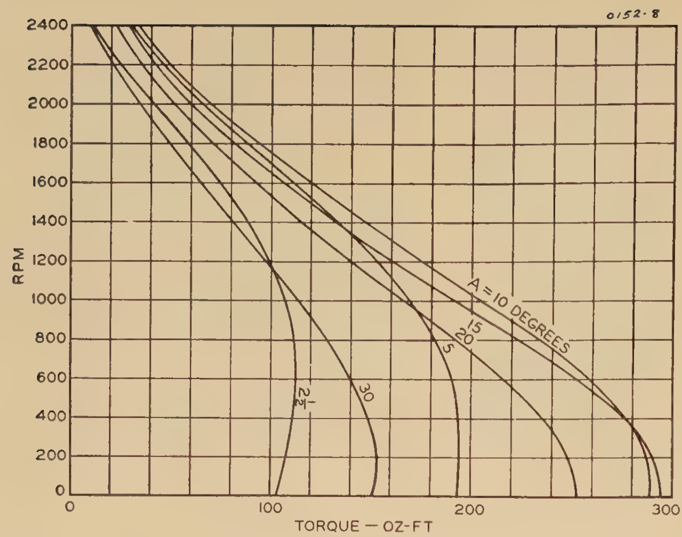


Figure 8. Effect of brush shift on speed-torque curves

A = Brush shift in electrical degrees

Then

$$I_1=E\frac{\dfrac{r_2r_3}{(X_m+x_2)^2}-\dfrac{(1-S^2)(X_m+x_2)^2}{(X_m+x_2)^2}+j\dfrac{(r_2+r_3)(X_m+x_2)}{(X_m+x_2)^2}}{U+jW}$$

$$I_2=\frac{EX_m}{(X_m+x_2)}\,\frac{\dfrac{-Sr_3\sin A}{X_m+x_2}-(1-S^2)\dfrac{X_m+x_2}{X_m+x_2}\times\cos A+j\dfrac{r_3}{X_m+x_2}\cos A}{U+jW}$$

$$I_3=\frac{EX_m}{(X_m+x_2)}\,\frac{\dfrac{Sr_2}{X_m+x_2}\cos A-(1-S^2)\times\dfrac{X_m+x_2}{X_m+x_2}\sin A+j\dfrac{r_2}{X_m+x_2}\sin A}{U+jW}$$

$$T=\frac{\dfrac{E^2X_m^2}{(X_m+x_2)^2}}{U^2+W^2}\left\{\frac{(r_3^2-r_2^2)(X_m+x_2)}{(X_m+x_2)^2}\times\sin A\cos A+[r_3\sin^2A+r_2\cos^2A]\times\left[-S\frac{r_2r_3}{(X_m+x_2)^2}+S(1-S^2)\frac{(X_m+x_2)^2}{(X_m+x_2)^2}\right]\right\}$$

where

$$U=-r_2\frac{X_m^2}{(X_m+x_2)^2}\cos^2A-r_3\frac{X_m^2}{(X_m+x_2)^2}\times\sin^2A-\frac{(r_2+r_3)(x_1+x_2)X_m}{(X_m+x_2)^2}-\frac{(r_2+r_3)x_1x_2}{(X_m+x_2)^2}+\frac{r_1r_2r_3}{(X_m+x_2)^2}-(1-S^2)r_1\frac{(X_m+x_2)^2}{(X_m+x_2)^2}$$

$$W=\frac{r_1(r_2+r_3)(X_m+x_2)}{(X_m+x_2)^2}+\frac{r_2r_3(X_m+x_1)}{(X_m+x_2)^2}+\frac{S(r_3+r_2)X_m^2\sin A\cos A}{(X_m+x_2)^2}-(1-S^2)\times\frac{(X_m+x_2)}{(X_m+x_2)^2}[X_m(x_1+x_2)+x_1x_2]$$

$$\Phi_f=\frac{\sqrt{2}I_3(X_m+x_2)}{2\pi fN10^{-8}}\left[\frac{X_m}{(X_m+x_2)}\frac{I_1}{I_3}\sin A-1\right]$$

$$\Phi_t=\frac{\sqrt{2}I_2(X_m+x_2)}{2\pi fN10^{-8}}\left[\frac{X_m}{(X_m+x_2)}\frac{I_1}{I_2}\cos A-1\right]$$

From this point on, we will depart from Mr. West's derivation, and method of attack. For simplicity of calculation, and so that the designer may know just how the motor losses are distributed, we will calculate the magnitudes alone of the currents, and obtain the input from the sum of output and losses. In order to simplify the above equations, let us arbitrarily define

$$X_0=X_m+x_2$$

$$K_p=\frac{X_m}{X_m+x_2}=\frac{X_m}{X_0}$$

$$K_r=K_p^2=\frac{X_m^2}{X_0^2}=\frac{X_m^2}{(X_m+x_2)^2}$$

$$I_1=E\frac{\dfrac{r_2}{X_0}\dfrac{r_3}{X_0}-(1-S^2)+j\dfrac{(r_2+r_3)}{X_0}}{U+jW}$$

$$I_2=EK_p\frac{-S\dfrac{r_3}{X_0}\sin A-(1-S^2)\cos A+j\dfrac{r_3}{X_0}\cos A}{U+jW}$$

$$I_3=EK_p\frac{S\dfrac{r_2}{X_0}\cos A-(1-S^2)\sin A+j\dfrac{r_2}{X_0}\sin A}{U+jW}$$

$$T=\overline{EK_p}^2\left\{\frac{\dfrac{(\sqrt{r_3^2-r_2^2})^2}{X_0}\sin A\cos A+[r_3\sin^2A+r_2\cos^2A]\times\left[-S\dfrac{r_2r_3}{X_0X_0}+S(1-S^2)\right]}{U^2+W^2}\right\}$$

$$U=-r_2K_r\cos^2A-r_3K_r\sin^2A-\frac{(r_2+r_3}{X_0}\left[\frac{x_1X_m+x_2X_m+x_1x_2}{(X_m+x_2)}\right]+\frac{r_1r_2r_3}{X_0X_0}-(1-S^2)r_1$$

$$W=\frac{r_1(r_2+r_3)}{X_0}+\frac{r_2r_3}{X_0}\frac{(X_m+x_1)}{(X_m+x_2)}+S(r_3-r_2)K_r\sin A\cos A-(1-S^2)\left[\frac{x_1X_m+x_2X_m+x_1x_2}{X_m+x_2}\right]$$

$$\Phi_{f\max}=I_3X_0\left(\frac{I_1}{I_3}K_p\sin A-1\right)\frac{45\times10^6}{fCK_w}$$

$$\Phi_{t\max}=I_2X_0\left(\frac{I_1}{I_2}K_p\cos A-1\right)\frac{45\times10^6}{fCK_w}$$

(It must be remembered that the currents are vectors in these equations.)

Let us now define

$$i_m=\frac{E}{X_0}$$

$$X=x_1+x_2K_p=\frac{x_1X_m+x_2X_m+x_1x_2}{X_m+x_2}$$

Then

$$I_1=\frac{i_mr_2\dfrac{r_3}{X_0}-E(1-S^2)+ji_m(r_2+r_3)}{U+jW}$$

$$I_2=\frac{-Si_mr_3K_p\sin A-(1-S^2)EK_p\cos A+ji_mr_3K_p\cos A}{U+jW}$$

$$I_3=\frac{Si_mr_2K_p\cos A-(1-S^2)EK_p\sin A+ji_mr_2K_p\sin A}{U+jW}$$

The torque equation is not affected by these last simplifications.

$$U=-(1-S^2)r_1-r_2K_r\cos^2A-r_3K_r\sin^2A-\frac{r_2+r_3}{X_0}X+\frac{r_1r_2r_3}{X_0^2}$$

$$W=-(1-S^2)X+S(r_3-r_2)K_r\sin A\cos A+r_1\frac{r_2+r_3}{X_0}+\frac{r_2r_3(X_m+x_1)}{X_0(X_m+x_2)}$$

In motors of normal proportions, r_3 is very large, and often as a check, a calculation is made with r_3 increased to infinity. This is a convenient way to tell whether the brush resistance is as large as it ought to be. Let us divide both numerator and denominator of the current equations by $-r_3$ and the torque equation by $(-r_3)^2$. This will cause the terms affected by the useless brush short-circuit current, to become smaller and smaller as r_3 approaches infinity.

$$U=(1-S^2)\frac{r_1}{r_3}+\frac{r_2}{r_3}K_r\cos^2A+K_r\sin^2A+\frac{X}{X_0}\left(1+\frac{r_2}{r_3}\right)-\frac{r_1r_2}{X_0X_0}$$

$$W=(1-S^2)\frac{X}{r_3}-S\left(1-\frac{r_2}{r_3}\right)K_r\sin A\cos A-\frac{r_1}{X_0}\left(1+\frac{r_2}{r_3}\right)-\frac{r_2}{X_0}\frac{(X_m+x_1)}{(X_m+x_2)}$$

$$I_1=\frac{(1-S^2)\dfrac{E}{r_3}-\dfrac{i_mr_2}{X_0}-ji_m\left(1+\dfrac{r_2}{r_3}\right)}{U+jW}$$

Figure 12. Calculation sheet for repulsion motors

E	220	X_o	62.8
X	5.48	i_m	3.50
K_p	.955	K_r	.914
r_1 hot	1.10	r_{2i} hot	2.70
Brush	3/16 x 3/4		
N_c	64	A_B	.1166
a	4	r_b	.009
		$[DF_{2i}/DF_3]^2$	.406
$R_A = \frac{r_c N_c}{a}$	1.044	r_c hot	.0653
$R_B = \frac{r_b 4}{A_B}$	.308	R_B	.308
$R_A + R_B$	1.352	$r_c + R_B$	.3733
$r_2 = r_{2i}\frac{R_A+R_B}{R_A}$	3.50	r_3	100.
r_2/X_o	.0557	r_2/r_3	.035
X/X_o	.0872	$1 + r_2/r_3$	1.035
r_1/X_o	.0175	$1 - r_2/r_3$	.965
r_1/r_3	.011	X/r_3	.0548

A	Brush Shift	15°
	Sin A	.259
	Cos A	.966
C	Sin A Cos A	.250
	$(r_2/r_3)\cos^2 A$	.0327
	$\sin^2 A$	.0671
B	$(r_2/r_3)\cos^2 A + \sin^2 A$	.0998
	$(r_1/X_o)(1 + r_2/r_3)$	.0181
	r_2/X_o	.0557
H_1	$(r_1/X_o)(1+r_2/r_3) + r_2/X_o$	.0738
	$\frac{X}{X_o}(1 + r_2/r_3)$	.0902
	$K_r B$	.0912
H_2	$\frac{X}{X_o}(1+r_2/r_3) + K_r B$	.1814
H_3	$K_r C(1 - r_2/r_3)$	.221
H_{10}	$i_m(1 + r_2/r_3)$	3.62
H_{11}	$E H_3 H_{10}$	175.8
H_{14}	$(EK_p)^2 B/r_3$	44.0
H_7	$(i_m^2 r_2)(K_r B)$	3.92
H_8	$i_m K_p \cos A$	3.23
H_5	$H_8\, r_2/r_3$	.113
H_9	$i_m K_p \sin A$	.866
H_6	$H_9\, r_2/r_3$	.0303
H_{12}	$(E/r_3) K_p \cos A$	2.03
H_{13}	$(E/r_3) K_p \sin A$	.554
H_4	$i_m r_2/X_o$	.195

1	S = RPM/SYN	0	.1	.25	.50	.75	1.00	1.25
2.	S^2	0	.01	.0625	.25	.561	1.00	1.563
3	$(1-S^2)$	1.00	.99	.938	.75	.439	0	−.563
4	(3) x r_1/r_3	.0110	.0109	.0103	.0083	.0048	0	−.0062
5	H_2	.1814	.1814	.1814	.1814	.1814	.1814	.1814
6	U = (4) + (5)	.1924	.1923	.1917	.1897	.1862	.1814	.1752
7	(3) x X/r_3	.0548	.0543	.0515	.0411	.0241	0	−.0309
8	SH_3	0	.0221	.0553	.1105	.1658	.211	.276
9	(7) − (8)	.0548	.0322	−.0038	−.0694	−.1417	−.211	−.3069
10	H_1	.0738	.0738	.0738	.0738	.0738	.0738	.0738
11	W = (9) − (10)	−.0190	−.0416	−.0776	−.1432	−.2155	−.295	−.381
12	$\sqrt{U^2+W^2}$	.193	.197	.207	.238	.285	.346	.419
13	(3) x E/r_3	2.20	2.18	2.06	1.65	.965	0	−1.24
14	H_4	.195	.195	.195	.195	.195	.195	.195
15	(13) − (14)	2.005	1.985	1.865	1.455	.770	−.195	−1.435
16	$\sqrt{(15)^2 + H_{10}^2}$	4 14	4.13	4.08	3.91	3.70	3.63	3.89
17	I_1 = (16)/(12)	21.5	21.0	19 7	16.4	13 0	10.5	9.28
18	(3) x H_{12}	2.03	2.01	1.905	1.523	.890	0	−1.143
19	SH_9	0	.087	.217	.433	.650	.866	1.083
20	(18) + (19)	2.03	2.10	2.122	1.956	1.540	.866	−.060
21	$\sqrt{(20)^2 + H_8^2}$	3.82	3.85	3.87	3.78	3.58	3.34	3.23
22	I_2 = (21)/(12)	19.8	19.6	18.7	15.9	12.56	9.65	7.71
23	(3) x H_{13}	.554	.549	.520	.416	.244	0	−.312
24	SH_5	0	.0113	.0283	.0565	.0847	.113	.141
25	(23) − (24)	.554	.538	.492	.359	.159	−.113	−.453
26	$\sqrt{(25)^2 + H_6^2}$	.554	.538	.492	.360	.162	.117	.454
27	I_3 = (26)/(12)	2.83	2.73	2.38	1.51	.568	.338	1.083
28	(3) x H_{14}	—	43.6	41.3	33.0	19.3	0	−24.8
29	H_7	—	3.9	3.9	3.9	3.9	3.9	3.9
30	(28) − (29)	—	39.7	37.4	29.1	15.4	−3.9	−28.7
31	S x (30)	0	3.97	9.35	14.56	11.56	−3.9	−35.9
32	H_{11}	175.8	175.8	175.8	175.8	175.8	175.8	175.8
33	(31) + (32)	175.8	179.8	185.2	190.4	187.4	171.9	139.9
34	$(33)/(12)^2$	4720	4640	4320	3360	2300	1435	796
35	Fe + F & W	0	1.	7	27	62	110	172
36	Syn. Watts = (34) − (35)	4720	4639	4313	3333	2238	1325	624
37	RPM = S x Syn	0	180	450	900	1350	1800	2250
38	Torque = $\frac{112.7}{SYN}$ x (36)	295	291	270	209	140	83	39
39	Output = S x (36)	0	464	1079	1667	1680	1325	780
40	Prim Loss = $I_1^2 r_1$	507	486	428	297	186	121	95
41	Sec Loss$_m$ = $I_2^2 r_2$	1370	1340	1225	883	552	327	208
42	Sec. Loss$_c$ = $I_3^2 r_3$	825	749	564	229	32	11	117
43	Tot. Loss = (35)+(40)+(41)+(42)	2702	2576	2234	1436	832	579	592
44	Input = (39) + (43)	2702	3040	3313	3103	2512	1904	1372
45	Eff = (39)/(44)	0	15.3	32.5	53.7	66.9	69.5	56.8
46	P.F. = (44)/EI_1	57.2	65.8	76.4	87.6	87.8	82.3	67.2
47	H.P. Output	0	.611	1.446	2.23	2.25	1.776	1.046
48								
49								
50								
51								
52								

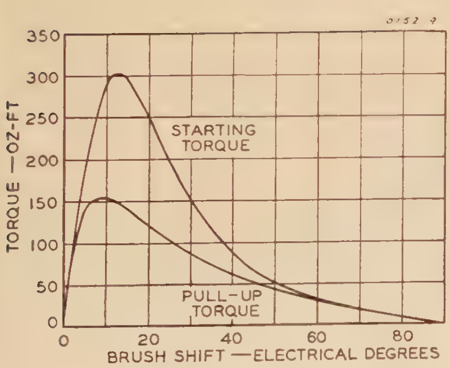


Figure 9. Effect of brush shift on starting and pull-up torques

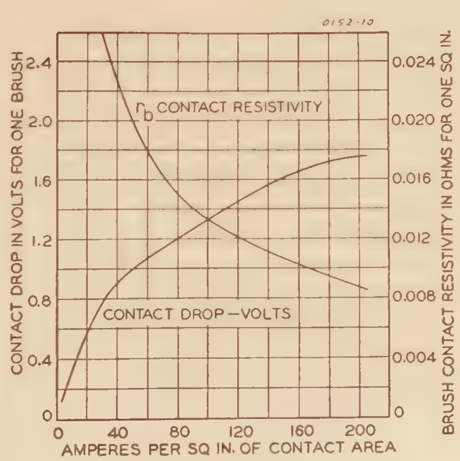


Figure 10. Typical brush resistance and volt-ampere curves

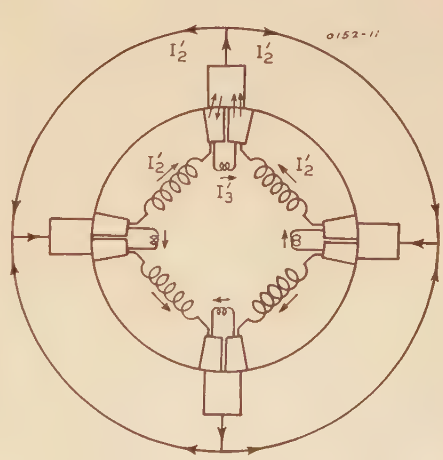


Figure 11. Schematic diagram of secondary circuit of repulsion motor

$$I_2=\frac{(1-S^2)\dfrac{E}{r_3}K_p\cos A+Si_mK_p\sin A-ji_mK_p\cos A}{U+jW}$$

$$I_3=\frac{(1-S^2)\dfrac{E}{r_3}K_p\sin A-Si_m\dfrac{r_2}{r_3}K_p\cos A-ji_m\dfrac{r_2}{r_3}K_p\sin A}{U+jW}$$

$$T=\frac{S\left\{(1-S^2)\left[\dfrac{\overline{EK_p}^2}{r_3}\left(\dfrac{r_2}{r_3}\cos^2 A+\sin^2 A\right)\right]-\left(\dfrac{EK_p}{X_0}\right)^2 r_2\left(\dfrac{r_2}{r_3}\cos^2 A+\sin^2 A\right)\right\}}{U^2+W^2}+\frac{\dfrac{\overline{EK_p}^2}{X_0}\sin A\cos A\left[1-\left(\dfrac{r_2}{r_3}\right)^2\right]}{U^2+W^2}$$

For purposes of calculation, let us arrange the terms in each equation into groups, those terms which are a function of speed in one group, and those which are independent of speed in another group.

$$U=(1-S^2)\frac{r_1}{r_3}+H_2$$

where

$$H_2=K_rB+\frac{X}{X_0}\left(1+\frac{r_2}{r_3}\right)-\frac{r_1r_2}{X_0X_0}$$

(This last term $\dfrac{r_1r_2}{X_0X_0}$ is usually negligible)

$$B=\frac{r_2}{r_3}\cos^2 A+\sin^2 A$$

$$W=(1-S^2)\frac{X}{r_3}-SH-H_1$$

$$H_3=K_r\left(1-\frac{r_2}{r_3}\right)C$$

$$C=\sin A\cos A$$

$$H_1=\frac{r_1}{X_0}\left(1+\frac{r_2}{r_3}\right)+\frac{r_2}{X_0}\frac{(X_m+x_1)}{(X_m+x_2)}$$

(The term $\dfrac{(X_m+x_1)}{(X_m+x_2)}$ can usually be taken as unity)

$$I_1=\frac{(1-S^2)\dfrac{E}{r_3}-H_4-jH_{10}}{U+jW}$$

$$H_4=\frac{i_mr_2}{X_0}$$

$$H_{10}=i_m\left(1+\frac{r_2}{r_3}\right)$$

$$I_2=\frac{(1-S^2)H_{12}+SH_9-jH_8}{U+jW}$$

$$H_{12}=\frac{E}{r_3}K_p\cos A$$

$$H_9=i_mK_p\sin A$$

$$H_8=i_mK_p\cos A$$

$$I_3=\frac{(1-S^2)H_{13}-SH_5-jH_6}{U+jW}$$

$$H_{13}=\frac{E}{r_3}K_p\sin A$$

$$H_5=i_m\frac{r_2}{r_3}K_p\cos A$$

$$H_6=i_m\frac{r_2}{r_3}K_p\sin A$$

Torque in synchronous watts=

$$\frac{S[(1-S^2)H_{14}-H_7]+H_{11}}{U^2+W^2}$$

$$H_7=i_m^2r_2K_rB$$

$$H_{11}=EH_{10}H_3$$

$$H_{14}=\overline{EK_p}^2\frac{B}{r_3}$$

Output$=S$ times torque in synchronous watts

Torque in ounce-feet $=\dfrac{112.7}{\text{synchronous rpm}}$ times torque in synchronous watts

By arranging the calculation of these terms in proper sequence, a simple and straightforward calculation sheet may be obtained. Such a calculation sheet is shown in figure 12.

Appendix II

Derivation of the Equations of Rotor Resistance

The secondary resistance of the armature of a repulsion motor must be calculated for two separate conditions when operating repulsion, and for a third condition when operating induction in a repulsion-start, induction-run motor. In all cases, the problem is to obtain the effective secondary resistance, referred to the primary, of a motor which for this problem may be considered as a transformer. Since the resistances of a transformer may be transferred from primary to secondary or vice versa by multiplying by the square of the transformation ratio, the problem becomes one of correctly determining the actual secondary resistance, and the transformation ratio.

Let

"ratio" = transformation ratio squared
r_s = actual secondary resistance
r_c = resistance per coil
N_c = total number of coils on armature
r_2 = secondary resistance referred to the primary
a = the number of parallel paths in the secondary

$$\text{"ratio"}=\frac{(CK_{wm})^2}{(CK_{w2})^2}$$

where

CK_{wm} = effective series conductors of the primary
CK_{w2} = effective series conductors of the secondary
K_w = winding factor (pitch times distribution factor)

Then

r_2 = "ratio" times r_s

Case I

Repulsion-start, induction-run motor operating induction with all bars of the commutator short-circuited.

$r_{st}=r_c/N_c$
$CK_{w2}=2\,tpc\,K_{w2t}$ (K_{w2t} is usually close to 0.637)
tpc = turns per coil on the armature

Case II

Normal repulsion motor, r_2 = resistance of main phase or useful part of the armature.

$$r_{s2}=\frac{\dfrac{r_cN_c}{a}+\dfrac{r_b4}{A_b}}{a}$$

where

N_c/a = number of coils between brushes
r_b = resistance per square inch of brush contact
A_b = brush contact area in square inches (minus that area of the brush in contact with mica)

$CK_{w22}=\dfrac{2\,tpc\,N_cK_{w22}}{a}$ (K_{w22} is usually close to 0.637)

It can be shown that if r_b equal zero, $r_{st}=r_{s2}$. Thus

$$r_2=r_{2t}\frac{R_A+R_B}{R_A}$$

Where

$$R_A=\frac{r_cN_c}{a}\text{ and }R_B=\frac{r_b4}{A_b}$$

Case III

Normal repulsion motor, r_3 = secondary resistance of the short-circuited coils.

$$r_{s3}=\frac{r_c+\dfrac{r_b4}{A_b}}{a}$$

$CK_{w3}=2\,tpc\,K_{w3}$ (K_{w3} is usually equal to the armature chord factor, for with the brush spanning two bars only, and the one coil connected to these bars in one slot only, the distribution factor will be unity)

A convenient method calculating r_3 is to write the formula in terms of r_{2t}

$$r_3=r_{2t}\frac{(K_{w2t})^2}{(K_{w3})^2}\frac{r_c+R_B}{r_c}\frac{N_c}{a}$$

But the chord factor is the same for either case, therefore

$$r_3=r_{2t}\left\{\frac{r_c+R_B}{r_c}\frac{N_c}{a}\left[\frac{DF_{2t}}{DF_3}\right]^2\right\}$$

where

DF_{2t} = distribution factor of short-circuited rotor, usually about 0.637
DF_3 = distribution factor of the coil short-circuited by the brush, usually unity

$$DF=\frac{\sin n\theta/2}{n\sin\theta/2}$$

where

n = number of coils
θ = angle between coils in electrical degrees

Performance Calculations on Capacitor Motors

The Revolving-Field Theory

P. H. TRICKEY
MEMBER AIEE

Synopsis: A method is presented whereby the equations of capacitor motor performance calculation as developed by Mr. W. J. Morrill,[1] are arranged in a calculation sheet or form for use in routine design work.

IN 1929, W. J. Morrill presented his classic paper on "The Revolving Field Theory of the Capacitor Motor", giving the complete equations for calculating the performance and torque of a capacitor motor at any value of slip.

The equations are straightforward, but involve vector operations, and are rather slow for routine design work. Since 1929, many engineers have used the method, and have devised different methods of doing the many numerical operations necessary to obtain a final solution. The methods have varied from one extreme to the other, some engineers using the equations directly as written making each vector operation as necessary, and others working up a calculation sheet where all operations were numerical.

Paper 40-153, recommended by the AIEE committee on electrical machinery, and presented at the AIEE Middle Eastern District meeting, Cincinnati, Ohio, October 9–11, 1940. Manuscript submitted May 2, 1939; made available for preprinting September 4, 1940.

P. H. Trickey is section head, fractional-horsepower motor design, Diehl Manufacturing Company, Elizabethport, N. J.

Although engineers as a rule are perfectly capable of handling vector operations, most of those involved in motor design work, feel that any great number of vector operations in the midst of routine work, brings considerable risk of errors, and they like to avoid vectors where possible. The writer has developed a calculation sheet for using these formulas, where all the operations except the last in calculating the currents are performed without vectors. This seems to be a fairly satisfactory compromise between the difficulties of either extreme, and has worked out quite well in practice.

Calculation Sheet for Mr. Morrill's Equations

Figures 1 and 2 show pages 1 and 2 of the calculation method. As in Mr. Morrill's paper, the method consists of determining the currents in each branch circuit and their angles with the voltage. With these values, the torque, output, and losses may be determined. Figure 1 is taken up with the calculation of currents, and figure 2 with calculation of torque and performance. The first part of figure 1 covers the calculation of the apparent resistance and reactance of the secondary circuit to the forward and backward fields.

It will be noted that many of the terms and expressions in the equations are of very similar form. Advantage has been taken of this to arrange the sheet so that the operations are performed in two columns in such a way that the numbering of the operations is nearly the same. That is, operations 1, 2, 3, 4, etc. are exactly the same in form as operations 101, 102, 103, and 104. Upon reaching operation 13 and 113, it becomes necessary to cross from one column to the other occasionally, but the same essential similarity between the two columns is kept.

Iron Loss

A slightly different method of accounting for iron loss is used than that of Mr. Morrill. Mr. Morrill's equations neglect iron loss and then correct for it by adding it to the friction and windage losses as a reduction in output.

The writer has found that a closer comparison between calculated values and tested values may be obtained, if a slightly different method of iron loss correction is used. As with Mr. Morrill, the vector operations of items 35, and 37 give fictitious values of current which have been obtained while neglecting iron loss entirely. These fictitious values are used in calculating the internal torque and output. The friction, windage, and odd-frequency iron losses are then sub-

---

Brush Contact Resistance

The equations for secondary resistance contain a term which is a function of the contact drop at the brush and commutator. The resistance of the contact is determined by a number of things. First, the type of brush, second the current density, and in addition to these factors it is affected by the speed and temperature of the commutator. A typical brush resistance curve as a function of current density is shown in figure 10. It is furnished through the courtesy of the National Carbon Company. It will be noted that the curve has been extended beyond the conditions of normal continuous operation. This is done because motors designed for repulsion operation during the starting period only, have small brushes, and abnormally high current densities. These densities are likely to be between 100 and 300 amperes per square inch at the standstill condition.

As mentioned above, in order to be exact, it would be necessary to use a different value of brush resistance for each point of a calculated speed-torque curve. However, for practical cases, it is usually sufficiently accurate, to use the starting current density throughout the entire range of the caclulation.

Actual Secondary Currents

Figure 11 illustrates the conditions occurring at the brush, with the useful currents entering the brush from adjacent commutator bars, and the short-circuit current entering from one bar and leaving by way of the next bar. It may happen in some cases, that the short-circuit current is even greater than the useful current. For convenience, the actual values of the currents are given below.

$$I_2' = I_2 \frac{CK_{wm}}{CK_{w2}} \frac{1}{a}$$

$$I_3' = I_3 \frac{CK_{wm}}{CK_{w3}} \frac{1}{a}$$

Reactance Voltage

Since r_3 is so much greater than the reactance of the short-circuited coils, the commutation voltage referred to the primary is simply $I_3 r_3$. However, the actual voltage commutated by the brush must be obtained from the transformation ratio, that is,

$$E_c = I_3 r_3 \frac{2tpcK_{w3}a}{CK_{wm}}$$

Bibliography

1. The Cross-Field Theory of Alternating-Current Machines, H. R. West. AIEE Transactions, February 1926, page 466.

2. Performance Calculations on Induction Motors, C. G. Veinott. AIEE Transactions, September 1932, page 743.

$X_{1m} = \frac{X}{1+K_p}$ = X_{1m}	15.0	$K_r = \frac{X_o - X}{X_o} = \left(\frac{X_m}{X_m+X_2}\right)^2$	.842	r_{1m}	11.68	r_{1a}	8.812	60 Cy Fe	14.0
$X_2K_p = X_{1m}K_p$ = X_2K_p	13.7	$K_p = \sqrt{K_r} = \frac{X_m}{X_m+X_2}$	.917	r_2	38.4	R_c	.305	Hi Cy Fe	13.9
$X_o = X_o = X_m + X_2$	182.1	$K = CK_{wa}/CK_{wm}$	.763	r_2K_r	32.4	$X_{1a} = K^2X_{1m}$	8.75	F+W	3.1
$X_oK_p = X_oK_p$ = X_m	167	K^2	.583	r_2/X_o	.211	X_c (12.74 mfd)	-208	HyCy+FW	17.0

	Speed	1185	1042	830	500	120		Speed	1185	1042	830	500	120
1	s = slip	.0125	.1318	.3085	.583	.900	101	$2 - s$	1.988	1.868	1.692	1.417	1.10
2	$1/s$	80.0	7.60	3.24	1.716	1.111	102	$\frac{1}{2-s}$	.503	.535	.591	.706	.91
3	(r_2/X_o) (2)	16.88	1.602	.684	.362	.234	103	(r_2/X_o) (102)	.106	.113	.1248	.149	.192
4	$(3)^2$	285	2.57	.468	.131	.055	104	$(103)^2$	.0112	.0127	.0156	.0222	.0369
5	(4) + 1	286	3.57	1.468	1.131	1.055	105	(104) + 1	1.011	1.013	1.016	1.022	1.037
6	(5) x 2	572	714	2.936	2.26	2.11	106	(105) x 2	2.022	2.026	2.032	2.044	2.074
7	(r_2K_r) (2)	259	246	104.8	55.5	36.0	107	(r_2K_r) (102)	16.3	17.3	19.1	22.8	29.5
8	(7)/(6) = R_f	4.52	34.5	35.7	24.5	17.08	108	(107)/(106) = R_b	8.05	8.55	9.41	11.16	14.2
9	$(r_2K_p)(r_2/X_o)(2)^2$	47,500	430	78.0	21.8	9.20	109	$(r_2K_p)(r_2/X_o)(102)^2$	1.88	2.12	2.60	3.70	6.16
10	(X_2K_p)	13.7	13.7	13.7	13.7	13.7	110	(X_2K_p)	13.7	13.7	13.7	13.7	13.7
11	(9) + (10)	47,514	443.7	91.7	35.5	22.9	111	(109) + (110)	15.58	15.82	16.3	17.4	19.86
12	(11)/(6) = X_f	83.1	62.2	31.3	15.68	10.85	112	(111)/(106) = X_b	7.68	7.82	8.02	8.50	9.58
13	R_f	4.52	34.5	35.7	24.5	17.08	113	X_f	83.1	62.2	31.3	15.68	10.85
14	R_b	8.05	8.55	9.41	11.16	14.20	114	X_b	7.68	7.82	8.02	8.50	9.58
15	$R_f - R_b$	-3.53	25.95	26.3	13.34	2.88	115	$X_f - X_b$	75.4	54.4	23.3	7.18	1.27
16	$R_f + R_b$	12.57	43.05	45.1	35.7	31.3	116	$X_f + X_b$	90.8	70.0	39.3	24.2	20.43
17	r_{1m}	11.68	11.68	11.68	11.68	11.68	117	X_{1m}	15.0	15.0	15.0	15.0	15.0
18	(16) + (17)	24.25	54.73	56.78	47.38	42.98	118	(116) + (117)	105.8	85.0	54.3	39.2	35.43
19	K (115)	57.5	41.5	17.8	5.48	.97	119	K (15)	-2.69	19.8	20.1	10.2	2.2
20	(18) + (19)	81.75	96.23	74.58	52.86	43.95	120	(118) - (119)	108.5	65.2	34.2	29.0	33.23
21	R_c	.305	.305	.305	.305	.305	121	X_c	-208	-208	-208	-208	-208
22	r_{1a}	8.812	8.812	8.812	8.812	8.812	122	X_{1a}	8.75	8.75	8.75	8.75	8.75
23	$\frac{R_c + r_{1a}}{K^2 (16)}$	7.33	25.1	26.3	20.8	18.26	123	$\frac{X_c + X_{1a}}{K^2 (116)}$	53.0	40.8	22.9	14.1	11.9
24	(21)+(22)+(23)	16.45	34.2	35.4	29.9	27.38	124	(121)+(122)+(123)	-146	-158	-176	-185	-187
25	(19) (=K115)	57.5	41.5	17.8	5.48	.97	125	(119) (=K15)	-2.7	19.8	20.1	10.2	2.2
26	(24) - (25)	-41.0	-7.3	17.6	24.4	26.4	126	(124) + (125)	-149	-138	-156	-175	-185
27	(18) x (24)	399	1870	2010	1420	1176	127	(18) x (124)	-3540	-8650	-10,000	-8,760	-8040
28	(118) x (-124)	15,430	13,440	9,550	7,250	6,630	128	(118) x (24)	1740	2900	1,923	1172	970
29	$(19)^2$	3310	1725	317	30	.94	129	(127) + (128)	-1800	-5750	-8077	-7588	-7070
30	(27)+(28)+(29)	19,139	17,035	11,877	8,700	7,807	130						
31	$(119)^2$	7.2	392	404	104	4.85	131	2 (19)(119)	-309	1643	715	111.9	4.27
32	(30) - (31)	19,132	16,643	11,473	8,596	7,802	132	(129) - (131)	-1491	-7393	-8792	-7700	-7075
33	(32)/E	83.2	72.4	49.8	37.4	34.0	133	(132)/E	-6.49	-32.2	-38.2	-33.5	-30.8
34	Fe Loss (60~) / E_m	.0608	.0608	—	—	—	134		—	—	—	—	—
35	A+jB = $\frac{(26)+j(126)}{(33)+j(133)}$	-.352	.622	—	—	—	135	j Term	-1.814	-1.63	—	—	—
36	I_{mh} = (34)+(35)	-.289	.683	—	—	—	136	I_{mv} = (135)	-1.814	-1.63	—	—	—
37	I_{ah} = $\frac{(24)+j(124)}{(33)+j(133)}$ (g+jh)	.873	.776	—	—	—	137	I_{av} = j Term	1.370	1.246	—	—	—
38	I_{Lh} = (36)+(37)	.584	1.459	—	—	—	138	I_{Lv} = (136)+(137)	-.444	-.384	—	—	—
39													
40	—	—	—	—	—	—		—	—	—	—	—	—

Figure 1. Calculation sheet for capacitor motors, page 1

	Speed in RPM	1185	1042	830	500	120
41	$V = \sqrt{(33)^2 + (133)^2}$	83.5	79.3	62.8	50.2	46
42	V^2	6980	6290	3950	2520	2110
43	$N_m = \sqrt{(26)^2 + (126)^2}$	154.6	138	157	177	187
44	$N_a = \sqrt{(20)^2 + (120)^2}$	136	116	82	59.9	55.0
45	(26) x (120)	-4450	-476	602	710	878
46	(126) x (20)	-12,200	-13,290	-11,640	-9,250	-8,120
47	(45) - (46)	7,750	12,814	12,242	9,960	8,998
48	N_m/V	1.85	1.74	2.50	3.52	4.07
49	N_a/V	1.63	1.46	1.307	1.193	1.196
50	$(48)^2$	3.42	3.04	6.24	12.4	16.5
51	$(K(49))^2$	1.54	1.24	.99	.83	.83
52	(50) + (51)	4.96	4.28	7.23	13.2	17.3
53	$2K \times (47)/V^2$	1.69	3.11	4.73	6.03	6.50
54	(52) + (53)	6.65	7.39	11.96	19.2	23.8
55	(52) - (53)	3.27	1.17	2.50	7.2	10.8
56	(54) x R_f	30.1	255	427	470	407
57	(55) x R_b	26.3	10.	23.6	80.3	153.4
58	(56) - (57)	3.8	245	403.4	389.7	253.6
59	$(1 - s)$ x (58)	3.76	213	279	162.5	25.4
60	Hi Cy Fe Loss + F+W	16.6	13	8.2	3.0	.2
61	Output Watts = (59) - (60)	-12.8	200	271	160	25.2
62	RPM = $(1 - s)$ x Syn	1185	1042	830	500	120
63	Torque = $\frac{112.7}{RPM}$ (61)	-1.22	21.5	36.8	35.9	23.7
64	$I_m = \sqrt{I_{mh}^2 + I_{mv}^2}$ = Mn. Ph Amps.	1.84	1.77			
65	$I_a = \sqrt{I_{ah}^2 + I_{av}^2}$ = Aux. Ph. Amps.	1.63	1.47			
66	$I_L = \sqrt{I_{Lh}^2 + I_{Lv}^2}$ = Line Amps	.734	1.51			
67	Pri Loss$_m$ = $I_m^2 r_{1m}$	39.5	36.5			
68	Pri Loss$_a$ = $I_a^2 r_{1a}$	23.3	19.0			
69	Sec Loss$_f$ = (56) x s	.4	33.6			
70	Sec. Loss$_b$ = (57)(2 - s)	52.2	18.7			
71	Cap. Loss = $I_a^2 r_c$	.8	.7			
72	60 c Fe Loss	14.0	14.0			
73	Hi Cy Fe Loss + F+W = (60)	16.6	12.8			
74	Total Losses	146.8	135.2			
75	Input = (61) + (74)	134.0	334.9			
76	Eff = (61)/(75)	—	59.3			
77	P.F. = (75)/EI_L or I_{LH}/I_L	79.2	96.5			
78	App. Eff = (76) x (77)	—	57.2			
79	Cap. Volts = $I_a \times Z_c$	339	306			
80	H.P. Output	-.0172	.268			
81						
82						
83						
84						
85						

Figure 2. Calculation sheet for capacitor motors, page 2

tracted to give the useful output. A close approximation to the true current is obtained by adding to the in-phase component of the main winding current a value of in-phase current obtained by dividing the fundamental-frequency iron loss by the voltage.

This method accounting for the iron loss is based on the fact that the fundamental-frequency iron losses are normally supplied by the stator and the odd-frequency losses of the surfaces and tooth pulsations are supplied by the rotating member with a corresponding loss of torque.

Performance Calculation

Credit should be given to C. G. Veinott of the Westinghouse Electric and Manufacturing Company for the essential form of figure 2. It should be noted that the fictitious values of the currents are used for calculating the torque and the corrected values for calculating the stator copper losses. The odd-frequency iron losses are subtracted from the gross output along with the friction and windage.

It is believed that more accuracy is secured by obtaining the input from the output plus losses rather than by multiplying the voltage and the in-phase component of the line current. However, it is usually wise to check the two methods against each other.

Appendix

It is well at this point to definitely state the object of the following derivations. It is simply this: Starting with Mr. Morrill's equations, the object is to develop a simple routine calculation form which will give the performance of a capacitor motor at any speed when the necessary impedances or motor constants are known. The desired form is one with which results of practical accuracy are obtained with a minimum amount of calculation time, and the least likelihood of errors. From the point of view of routine work, it is also desirable that the work may be easily resumed after interruptions such as telephone calls, interviews, etc.

Since the design engineer who works on single-phase motors is very likely to design split-phase, capacitor-start, repulsion, and capacitor-run motors, the symbols and form of the calculation sheet have been arranged in accordance with the single-phase performance method of C. G. Veinott[2] and with the repulsion motor method of the writer now in process of publication by the AIEE.

The three fundamental equations of Mr. Morrill are as follows:

$$\boldsymbol{I}_m=\boldsymbol{E}_m\left\{\frac{[R_c+a^2(R_{1s}+R_f+R_b)]+j[X_c+a^2(X_{1s}+X_f+X_b)]+ja[(R_f-R_b)+j(X_f-X_b)]}{\{[R_c+a^2(R_{1s}+R_f+R_b)]+j[X_c+a^2(X_{1s}+X_f+X_b)]\}\{(R_{1m}+R_f+R_b)+j(X_{1m}+X_f+X_b)\}-a^2[(R_f-R_b)+j(X_f-X_b)]^2}\right\} \quad (122)$$

$$\boldsymbol{I}_s=\boldsymbol{E}_m\left\{\frac{[(R_{1m}+R_f+R_b)+j(X_{1m}+X_f+X_b)]-ja[(R_f-R_b)+j(X_f-X_b)]}{\{[R_c+a^2(R_{1s}+R_f+R_b)]+j[X_c+a^2(X_{1s}+X_f+X_b)]\}\{(R_{1m}+R_f+R_b)+j(X_{1m}+X_f+X_b)\}-a^2[(R_f-R_b)+j(X_f-X_b)]^2}\right\} \quad (123)$$

$$\text{Torque(average)}=[I_m^2+a^2I_s^2][R_f-R_b]+2a[Ah-Bg][R_f+R_b] \quad (8)$$

where

$\boldsymbol{I}_m=A+jB$ and $\boldsymbol{I}_s=g+jh$

The rearrangement consists of the steps:

A. Rewriting the equations in the symbols of Mr. Veinott's paper.

B. Rewriting the equations for the forward and backward impedances.

C. Obtaining the current terms $A+jB$ and $g+jh$ in quotient form.

$$A+jB=\frac{(26)+j(126)}{(33)+j(133)}$$

and

$$g+jh=\frac{(20)+j(120)}{(33)+j(133)}$$

D. Rearranging the torque equation so that the components $(26)+j(126)$ and $(20)+j(120)$ may be used instead of $A+jB$ and $g+jh$. This allows the calculation of torque without any vector operations.

E. Adding an in-phase iron loss component to $A+jB$ to correct for stator iron loss.

F. Addition of phase currents to obtain the line current.

A. Rewriting the Equations in the Symbols of Mr. Veinott's Paper. (See Table I)

Table I

New Symbol	Old Symbol	Definition
K	a	Total effective series conductors in auxiliary phase / Total effective series conductors in main phase
r_{1a}	a^2R_{1s}	Primary resistance of auxiliary phase
x_{1a}	a^2X_{1s}	Primary leakage reactance of auxiliary phase
r_{1m}	R_{1m}	Primary resistance of main phase
r_2	$2R_2$	Total secondary resistance referred to primary of main phase
x_{1m}	X_{1m}	Primary leakage reactance of main phase
x_2	$2X_2$	Total secondary leakage reactance referred to primary of main phase
X_m	$2X_m$	Total magnetizing reactance of main phase
s	S	Slip in per unit of synchronism
I_a	I_s	Auxiliary phase current

$$\boldsymbol{I}_m=\boldsymbol{E}_m\left\{\frac{[R_c+r_{1a}+K^2(R_f+R_b)]+j[X_c+x_{1a}+K^2(X_f+X_b)]+jK[(R_f-R_b)+j(X_f-X_b)]}{\{[R_c+r_{1a}+K^2(R_f+R_b)]+j[X_c+x_{1a}+K^2(X_f+X_b)]\}\{(r_{1m}+R_f+R_b)+j(x_{1m}+X_f+X_b)\}-K^2[(R_f-R_b)+j(X_f-X_b)]^2}\right\}$$

$$\boldsymbol{I}_a=\boldsymbol{E}_m\left\{\frac{[(r_{1m}+R_f+R_b)+j(x_{1m}+X_f+X_b)]-jK[(R_f-R_b)+j(X_f-X_b)]}{\{[R_c+r_{1a}+K^2(R_f+R_b)]+j[X_c+x_{1a}+K^2(X_f+X_b)]\}\{(r_{1m}+R_f+R_b)+j(x_{1m}+X_f+X_b)\}-K^2[(R_f-R_b)+j(X_f-X_b)]^2}\right\}$$

$$T_{avg}=(I_m^2+K^2I_a^2)(R_f-R_b)+2K(Ah-Bg)(R_f+R_b)$$

B. Rewriting the Forward and Backward Impedances

Mr. Morrill's equation

$$R_f=\frac{X_m^2\,R_2/s}{(R_2/s)^2+(X_2+X_m)^2}=$$

Rewritten in symbols of Mr. Veinott

$$\frac{(X_m/2)^2\,(r_2/2)(1/s)}{(r_2/2)^2(1/s)^2+\left(\dfrac{x_2+X_m}{2}\right)^2}$$

Let us arbitrarily define

$$X_0=X_m+x_2,\quad K_p=X_m/(X_m+x_2),$$
$$K_r=K_p^2=X_m^2/X_0^2$$

Substitute these values and divide both numerator and denominator by $X_0^2/4$

$$R_f=\frac{1}{2}\,\frac{(r_2K_r)1/s}{[(r_2/X_0)(1/s)]^2+1}$$

R_b becomes the same equation with $(2-s)$ in place of s

$$R_b=\frac{1}{2}\,\frac{(r_2K_r)\;1/(2-s)}{[(r_2/X_0)(1/(2-s))]^2+1}$$

Mr. Morrill writes

$$X_f=\frac{X_m[(R_2/s)^2+X_2(X_2+X_m)]}{(R_2/s)^2+(X_2+X_m)^2}=$$

Rewritten in symbols of Mr. Veinott

$$\frac{(X_m/2)[(r_2/2s)^2+x_2(x_2+X_m)/4]}{(r_2/2s)^2+(x_2+X_m)^2/4}$$

Substitute $X_0=X_m+x_2$, $K_p=X_m/(X_m+x_2)$, divide both numerator and denominator by $X_0/4$, and rearrange

$$X_f=\frac{1}{2}\,\frac{x_2K_p+(r_2K_p)(r_2/X_0)(1/s)^2}{[(r_2/X_0)(1/s)]^2+1}$$

and

$$X_b=\frac{1}{2}\,\frac{x_2K_p+(r_2K_p)(r_2/X_0)(1/(2-s))^2}{[(r_2/X_0)(1/(2-s))]^2+1}$$

C. OBTAINING A+jB AND g+jh IN QUOTIENT FORM

It will be noted from the equations of I_m and I_a, that many of the groups of terms are the same. Let us rewrite them using a symbol for each group. For simplicity let us use for symbols the item numbers of the final calculation sheets figures 1 and 2. Our purpose is to obtain

$$A+jB=\frac{(26)+j(126)}{(33)+j(133)}$$

and

$$g+jh=\frac{(20)+j(120)}{(33)+j(133)}$$

Then, assigning a number symbol to each term, we obtain

$$A+jB=E_m\times\left\{\frac{(24)+j(124)+jK[(15)+j(115)]}{\{(24)+j(124)\}\{(18)+j(118)\}-K^2[(15)+j(115)]^2}\right\}$$

$$g+jh=E_m\times\left\{\frac{(18)+j(118)-jK[(15)+j(115)]}{\{(24)+j(124)\}\{(18)+j(118)\}-K^2[(15)+j(115)]^2}\right\}$$

Simplifying to obtain one real and one quadrature term in both numerator and denominator,

$$A+jB=E_m\times\left\{\frac{[(24)-K(115)]+j[(124)+K(15)]}{[(24)(18)-(124)(118)-K^2(15)^2+K^2(115)^2]+j[(18)(124)+(118)(24)-2(K15)(K115)]}\right\}$$

$$g+jh=E_m\times\left\{\frac{[(18)+K(115)]+j[(118)-K(15)]}{[(24)(18)-(124)(118)-K^2(15)^2+K^2(115)^2]+j[(18)(124)+(118)(24)-2(K15)(K115)]}\right\}$$

Assigning number symbols to the above groups of terms,

$$A+jB=E_m\frac{(26)+j(126)}{(32)+j(132)}$$

and

$$g+jh=E_m\frac{(20)+j(120)}{(32)+j(132)}$$

Dividing numerator and denominator by E_m gives the desired result

$$A+jB=\frac{(26)+j(126)}{(33)+j(133)}$$

and

$$g+jh=\frac{(20)+j(120)}{(33)+j(133)}$$

D. REARRANGING THE TORQUE EQUATION

$$T=(I_m^2+K^2I_a^2)(R_f-R_b)+2K(Ah-Bg)(R_f+R_b)$$

In order to avoid making the vector operation involved in obtaining A, B, g, and h, let

$$N_m=\sqrt{(26)^2+(126)^2}$$

$$N_a=\sqrt{(20)^2+(120)^2}$$

$$V=\sqrt{(33)^2+(133)^2}$$

Also since $(Ah-Bg)$ is the quadrature term obtained by multiplying $(g+jh)$ by the conjugate of $(A+jB)$, performing this operation on both right and left sides of the equations gives us an expression for $(Ah-Bg)$.

$$(A-jB)(g+jh)=(Ag+Bh)+j(Ah-Bg)$$

$$\frac{(26)-j(126)}{(33)+j(133)}\times\frac{(20)+j(120)}{(33)+j(133)}=\frac{[(26)(20)+(126)(120)]-j[(26)(120)-(126)(20)]}{(33)^2+(133)^2}$$

Thus

$$Ah-Bg=\frac{(26)(120)-(126)(20)}{V^2}$$

and

$$T=[(N_m/V)^2+(KN_a/V)^2](R_f-R_b)+2K\left[\frac{(26)(120)-(126)(20)}{V^2}\right](R_f+R_b)$$

This allows the calculation of torque without any vector operations, which is particularly desirable in calculating speed-torque curves, pull-up torque of capacitor-start motors, or in designing two- or three-speed fan motors.

E. CORRECTING FOR PRIMARY IRON LOSS

Although the fundamental frequency iron loss is supplied by the primary, and the odd-frequency iron loss by the rotor, it is not possible to include the stator iron loss in the primary part of the revolving field equations without making them too complicated. If the total iron loss is subtracted from the output similar to the friction and windage losses, it will be found in certain motors, particularly those designed for speed change driving low-horsepower fans, that the calculated useful torque will not agree with the tested value. The writer has had considerable success in approximating the true condition by simply adding an in-phase current component to the main phase current to account for the stator iron loss. This seems to agree with test much closer than adding half to the main phase and half to the auxiliary phase. The final main phase current is then

$$A+\frac{\text{fundamental-frequency iron loss}}{E_m}+jB$$

The auxiliary phase current is $g+jh$, and the line current is the vector sum.

In figure 1 the fundamental-frequency iron loss is denoted by the symbol "60 Cy Fe" and the odd-frequency iron loss by the symbol "Hi Cy Fe". $F+W$ is used as the symbol for friction and windage.

As a matter of interest, the motor used as an example for figure 1 is a one-fourth horsepower 230-volt 60-cycle six-pole single-value capacitor motor designed for three-speed unit-heater fan service to be used with an autotransformer for speed control.

Bibliography

1. THE REVOLVING FIELD THEORY OF THE CAPACITOR MOTOR, W. J. Morrill. AIEE TRANSACTIONS, April 1929, pages 614–29.

2. PERFORMANCE CALCULATIONS ON INDUCTION MOTORS, C. G. Veinott. AIEE TRANSACTIONS, September 1932, pages 743–55.

A New Current-Limiting Fuse

H. L. RAWLINS
ASSOCIATE AIEE

A. P. STROM
MEMBER AIEE

H. W. GRAYBILL
ASSOCIATE AIEE

Synopsis: Increasing concentration of power combined with the desire for more compact switchgear assemblies has created a demand for small, totally enclosed, high-interrupting-capacity fuses suitable for potential and operating transformer protection. The current-limiting fuse meets these requirements for it is inherently a high-interrupting-capacity fuse of low current rating and can be totally enclosed in a small space.

The theory and construction of previous current-limiting fuses are briefly described. The theory and construction of a new current-limiting fuse is given. The new fuse is simple in theory and construction. Its fundamental elements can be separated, studied, and tested, making it possible to predict an unusual degree of reliability and freedom from voltage surges. Test results confirm the reliability, high interrupting capacity, and freedom from voltage surges of the new fuse.

THE development and adoption of the first current-limiting fuses were prompted by the need for high interrupting ability. The other characteristics of the fuse were merely incidental and were not major factors in the wide acceptance of the current-limiting fuse in Europe. To limit the current and thereby limit the amount of energy liberated in the fuse was one way of obtaining high interrupting ability. In fact, before the advent of boric acid, as an interrupting medium, the current-limiting fuse was the only fuse that could safely be applied to many of the systems then in existence. During 1931 current-limiting fuses were imported, tested, and studied for possible adoption in this country where high interrupting ability was required. These fuses had the desirable features of high interrupting ability in a relatively small size and did not expel arc gases or other material during operation. However, the limited range of current ratings available in the fuse so restricted the scope of its application that its commercial development for use in this country was abandoned. Further development evolved the boric acid fuse with its high interrupting ability, totally enclosed features, and wide range of current ratings.

The increased use of metal-enclosed switchgear has placed a premium on space. The amount of room required for a low-interrupting-ability fuse with current-limiting resistor or a standard power fuse for the protection of potential or small operating transformers appears to

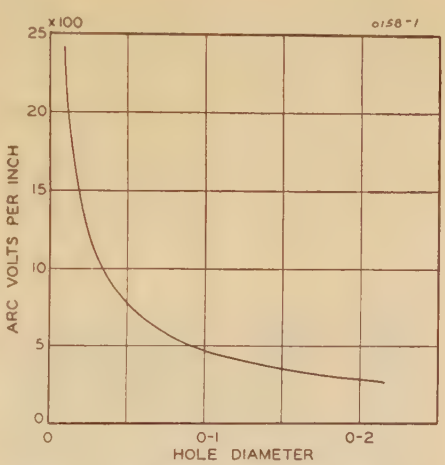


Figure 1. Characteristics of arcs in small holes

be all out of proportion to the size of the apparatus being protected and the load handled. It should be remembered, however, that the real duty of the fuse is to protect the system rather than the apparatus. There is a need, therefore, for a fuse having the small size and characteristics of the current-limiting fuse for connecting small loads to high-power systems as a supplement to power fuses that are used for heavier capacity loads.

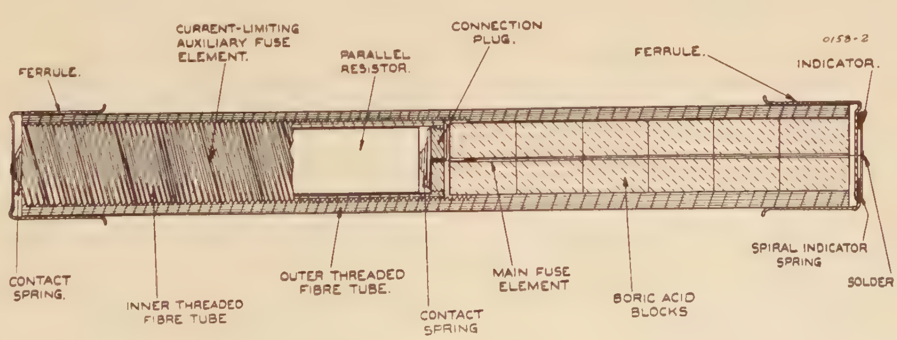
At the present time there are two types of current-limiting fuses available. One type consists of a fuse and resistor in series enclosed in a common cartridge. The resistor limits the current during the interruption of the fuse. The required characteristics of a resistor to carry load current and to limit the current on short circuit are directly opposed. To satisfactorily combine both characteristics in one resistor requires a relatively large resistor that necessitates a bulky cartridge.

The other type of current-limiting fuse consists of a silver wire spirally wound on a ceramic core and surrounded by inert crystals.[1,4] This type of fuse has had an excellent record in Europe for over a decade and in this country for two years. Characteristics of this fuse believed capable of improvement are:

1. It has a high melting temperature and, therefore, if made in higher ampere ratings would have a high operating temperature.
2. It offers no flexibility in obtaining time-current characteristics to meet various applications.
3. On operations at currents slightly above the melting point of the wire the operation may not be as reliable as in a spring-operated fuse.
4. The reliability of the fuse depends on the characteristics of the inert crystals used, therefore, a reliable source of supply and very rigid inspection are necessary to maintain the quality of the fuse.

Early tests on various forms of current-limiting fuses revealed high voltage surges during current limitation. Small variations in construction would result in widely different surge voltages. In order for a fuse to limit the current a voltage must be produced in the fuse equal to or greater than the voltage available in the circuit at the time of current limitation. Also the voltage produced must not rise to a value that might cause flashover or otherwise endanger the circuit on which it is applied. It is evident, therefore, that in order for a current-limiting fuse to be

Figure 2. Sectional view of new-type current-limiting fuse



Paper 40-158, recommended by the AIEE committee on protective devices, and presented at the AIEE Middle Eastern District meeting, Cincinnati, Ohio, October 9–11, 1940. Manuscript submitted August 13, 1940; made available for preprinting August 26, 1940.

H. L. RAWLINS is section engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., A. P. STROM is research engineer in the high-voltage laboratory of the company at Trafford, Pa., and H. W. GRAYBILL is design engineer in the switchgear engineering department of the company at East Pittsburgh.

1. For all numbered references, see list at end of paper.

reliable the voltage rise during current limitation must be accurately controlled and kept within a definite range. A further requirement of reliability is that the means for controlling the voltage rise should not be critical or susceptible to the small variations in size or material that are liable to occur in commercial production.

Investigations on arcing characteristics revealed that arcs drawn in small holes in

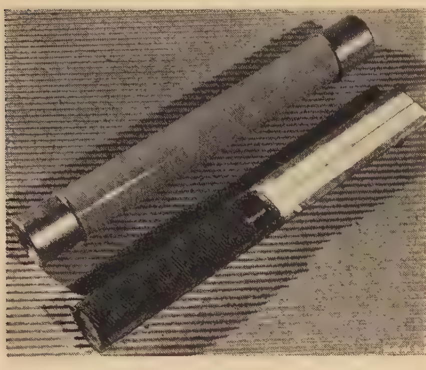


Figure 3. Photograph of new current-limiting fuse

solid material gave a high arc voltage that increased very rapidly as the size of the hole was reduced.[3] This characteristic is shown by the curve in figure 1. By utilizing a very small hole, a very high arc voltage and therefore a very definite current-limiting action can be obtained. The smaller the hole, the higher the arc voltage and the more reliable the current-limiting action will be, disregarding any possible danger to the system from the high voltage.

To limit the voltage on any device it is merely necessary to by-pass the current through a suitable resistor. This resistor may have a valve characteristic to limit the current at normal voltage and permit much higher currents to flow at higher voltages. If the fuse wire in a very small bore is paralleled with such a resistor, the basis is formed for a current-limiting fuse with a very definite and reliable current-limiting element and a very definite and reliable voltage-limiting element. A greater degree of reliability can be attained in such a device than in a device in which both the current and voltage are limited by the same element. If a clean-up fuse of proper characteristics is placed in series with such a combination, a complete current-limiting fuse is obtained. Such a fuse is shown in figures 2 and 3.

Construction and Operation

The essential elements of this new current-limiting fuse are:

1. *The Auxiliary or Current-Limiting Fuse Element.* This consists of a silver wire spirally wound on a multipitch threaded fiber tube which is screwed into a similarly threaded tube that forms the outer shell of the fuse holder. Fiber was selected for this purpose due to its gas-evolving properties and its mechanical strength although numerous tests have not demonstrated the need for any great mechanical strength in these parts. With gas-evolving material around the fuse element the arc voltage will be higher than with nongas-evolving materials. Furthermore, residual arc currents will be interrupted quickly with no possibility of a low-resistance path due to incandescent surfaces. The clearance left in the bottom of the thread after assembly provides a small hole slightly larger than the diameter of the wire, in which arc restriction occurs. On assembly a special cement is applied to the threads to form a seal between threads. Even with loose fitting parts the arc voltage produced in the restricted hole is many times the voltage required for current transfer to the parallel resistor rod.

2. *The Parallel Resistor Rod or Voltage-Limiting Element.* This element is a silicon-carbide rod of proper characteristics depending on the voltage rating, the current rating, and the interrupting rating of the fuse. It has a valve characteristic that becomes effective at currents approaching the interrupting rating of the fuse and limits the voltage rise at such currents to relatively safe values. This resistor is inside of the tube on which the auxiliary fuse element is

Figure 4. Dynamic volt-ampere characteristic of auxiliary fuse on 500-ampere 10x100-microsecond current wave

wound. Connection is made to it by means of contact springs. No special precautions are necessary in making contact with the resistor, as it passes current only during arc interruption, when full line voltage is impressed across the fuse.

3. *The Main Fuse Element.* This element, the clean-up element, is connected in series with the other elements of the fuse and serves as the final interrupter of all overcurrents that flow through the fuse. It also provides isolation after interruption. The fuse element operates in a small hole through solid boric acid. The excellent performance of boric acid in fuses both on low and high currents has been described in previous publications and has been demonstrated by many years in commercial use.[2] In the new current-limiting fuse this interrupting element is subjected to very easy service since it is called upon to open either extremely low currents or moderately low currents at a high power factor. The main fuse element itself is of the low-temperature type, can be designed to give any

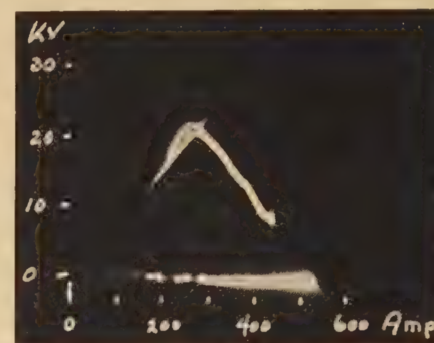


Figure 5. Dynamic volt-ampere characteristic of auxiliary fuse with parallel resistor rod on 500-ampere 10x100-microsecond current wave

desired time-current characteristics, and is spring operated to insure a positive gap on low-current operations. The spring that separates the fuse element also operates a suitable indicator that provides visual indication of a blown fuse.

The action of the fuse on low currents is not the same as on high currents due to the main fuse element being calibrated to melt at a lower current than the auxiliary fuse element. This was done to prevent any appreciable temperature rise of the auxiliary silver fuse wire and eliminate the possibility of the auxiliary fuse being melted before the main fuse. On low values of current the main fuse element may melt and interrupt the current without the auxiliary fuse wire being melted. In a fuse designed for potential-transformer protection this will happen on all currents below approximately 80 amperes. On high-current operation, the auxiliary fuse will melt on the initial rise in current and transfer the current to the parallel resistor rod. The thermal capacity of this rod is sufficient to permit a half cycle of current to pass through it without an excessive temperature rise. At the end of the first half cycle after current transfer the main fuse will interrupt the circuit.

Theory and Calculations

The operating characteristics of the current and voltage-limiting elements of

this fuse are of particular importance. Calculations can readily be made from which the performance of the device may be predicted.

When a short circuit occurs the current rises in the auxiliary fuse element with practically no limiting influence until the fuse element melts. At this point voltage rises rapidly to a high arc voltage and the current is limited and transferred to the resistor rod.

The maximum value which the current

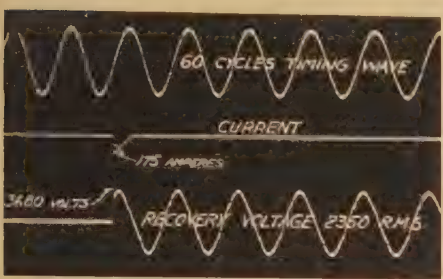


Figure 6. Operation of current-limiting fuse on a 2.3-kv system, with 20,000-ampere available short-circuit capacity

may reach when the fuse melts may be readily computed. Since the temperature rise of the fuse wire equals

$$\frac{\text{energy input}}{\text{mass}\times\text{specific heat}}$$

an infinitesimal temperature rise,

$$dT=\frac{i^2R(1+aT)dt}{Mk} \tag{1}$$

where

T = temperature, degrees centigrade
i = amperes
t = seconds
R = fuse resistance at zero degrees
a = temperature coefficient of resistance
M = mass of fuse wire, grams
k = watt seconds per gram per degree centigrade

The maximum rate of current rise occurs on symmetrical short circuits. Under such conditions we may, for simplicity and without appreciable error, assume that the current in the fuse wire up to the melting point is linear and equal to:

$$i=377I_mt \tag{2}$$

where I_m = maximum value of available 60-cycle short-circuit current.

We may then rewrite equation 1 as follows:

$$\frac{dT}{R(1+aT)}=\frac{(377)^2I_m{}^2}{Mk}t^2dt \tag{3}$$

Integrating equation 3, taking T between the limits of the initial fuse temperature, T_i, and the melting temperature, T_m, gives:

$$\frac{1}{Ra}\log_e\frac{1+aT_m}{1+aT_i}=\frac{(377)^2I_m{}^2}{Mk}\frac{t_m{}^3}{3} \tag{4}$$

whence time to the melting point,

$$t_m=\sqrt[3]{377I_m\cdot\frac{3Mk}{Ra}\log_e\frac{1+aT_m}{1+aT_i}} \tag{5}$$

Substituting this value of t in equation 2, gives the current at time of melting.

$$i_m=\sqrt[3]{377\,I_m\cdot\frac{3Mk}{Ra}\log_e\frac{1+aT_m}{1+aT_i}} \tag{6}$$

Whence

$$i_m=K\sqrt[3]{I_m}$$

This indicates that as the available system short-circuit current rises, the maximum value of the initial rush of short-circuit current in the fuse increases only as the cube root of the available short-circuit current. Thus, if the available short circuit increases from 10,000 to 80,000 amperes, the maximum value to which current can rise in the fuse will only double.

This is important since the initial voltage surge caused by the blowing of the fuse cannot exceed the product of the maximum initial fusing current times the resistance of the parallel resistor rod. It is, therefore, possible to design this fuse so as not to exceed any specified surge voltage. Since ordinary switching operations frequently cause voltage surges of twice the peak system voltage it is evident that the fuse may safely be designed to have twice peak value as an upper limit of surge voltage when the parallel fuse melts. Thus, if the fuse is designed to give a maximum surge voltage on a 10,000-ampere system, equal to peak voltage, then, since the surge varies as the cube root of the available system current, a short circuit on an 80,000-ampere system can be interrupted without exceeding a surge of twice the peak voltage. This indicates that a fuse of this type can cover a wide range of short-circuit currents without subjecting connected apparatus to excessive voltage surges.

As previously mentioned, it is further possible to make use of valve characteristics of the material in the parallel resistor rod, thus still further extending the range to which the fuse may be applied without excessive voltage surges.

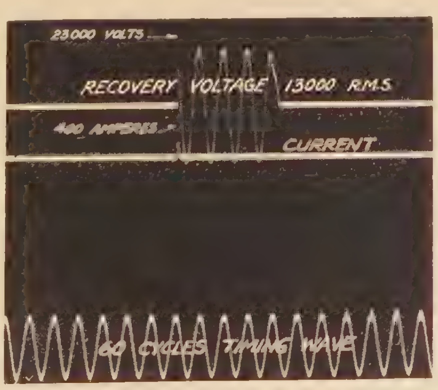


Figure 7. Operation of current-limiting fuse on a 13.2-kv system with 20,000-ampere available short-circuit capacity

Test Results

Important features of this fuse are the current-limiting fuse element and the voltage-limiting parallel resistor. The high arc voltage produced in the current-limiting fuse element and the effect of the parallel resistor in limiting that voltage are well illustrated in the oscillograms shown in figures 4 and 5. The tests represented by these oscillograms were made on a surge generator. Figure 4 shows the dynamic volt-ampere characteristics of the auxiliary fuse alone, while figure 5 shows the same characteristic of the auxiliary fuse and parallel resistor.

Numerous tests were made during the development of this fuse. Figures 6 and 7 show typical oscillograms of short-circuit interruptions on the fuse as finally perfected.

In figure 6 an interruption is shown on a 20,000-ampere 2,300-volt circuit. The fuse used in this test was similar to the illustration shown in figure 3, but of much smaller size, having an over-all length of only $4^5/_8$ inches. In this test it may be noted that the initial rush of current was limited at 175 amperes, while the surge voltage barely exceeded the peak value of the restored voltage.

Figure 7 shows an interruption on a 20,000-ampere 13.2-kv circuit. The fuse used in this test was as shown in figures

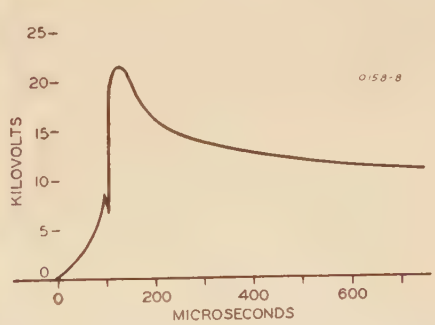


Figure 8. Cathode-ray oscillogram of voltage surge occurring on interruption shown in figure 7

An Electrical Governor

FRANK I. MORGAN
MEMBER AIEE

THE advantages obtained from the application of electrical methods of control to all classes of machinery, suggested to inventors the idea of regulating the speed of prime movers by electrical means. Frequent attempts have been made to accomplish this result. Many of these governors were very ingenious, but for one reason or another they never came into general use.

The electrical governor described in this paper is the result of several years effort to develop a practical method of electrically controlling and regulating the speed of hydraulic turbines.

Briefly, the method utilizes a form of frequency meter which measures variations in the frequency (corresponding to changes in speed) of an alternating current supplied by the generator driven by the turbine to be governed. This meter, through suitable control equipment, moves a pilot valve, which in turn controls the operating engine that opens or closes the wicket gates of the turbine.

An application of the scheme has been made to a 3,000-horsepower turbine operating under a head of 55 feet. The present installation is entirely experimental, the equipment being "home-made" and crude but the results obtained have been quite encouraging and indicate that the method has interesting possibilities.

A very steady speed is maintained at no load and synchronizing is done without difficulty with the governor in control of the unit. Operation under load is quite satisfactory, the governor responding promptly to small fractions of a cycle change in frequency (60 cycle). Changes in the loading of the machine are easily made, the governor responding instantly to such adjustments. Loads requiring gate openings of 80 to 90 per cent have been suddenly dropped by opening the generator circuit breaker. The governor closed the gates promptly and there was no tendency to "hunt" about the no-load position. Sudden accessions of load such as large "across the line" motors, are followed instantly by the opening of the turbine gates with no hunting whatever. The unit has been started from standstill many times by electrical remote control and when approximate normal speed was reached, placed under governor control by throwing a switch.

Some of the advantages of electrical governing are:

(*a*). Small inertia of the control element.

(*b*). Increased sensitivity.

(*c*). Elimination of long rods, cables, bell cranks, etc., required for the compensation devices of fly-ball governors.

(*d*). Since, with electrical control, the force operating the pilot valve can be made large, and is independent of the amount of the speed change, friction in this valve has little or no effect.

(*e*). The possibility of mounting the control element at any convenient location, such as on the main switchboard.

(*f*). The valve controlling the admission of pressure fluid to the servomotor can be mounted immediately on this cylinder thus reducing the amount of piping and releasing valuable floor space ordinarily required for governors.

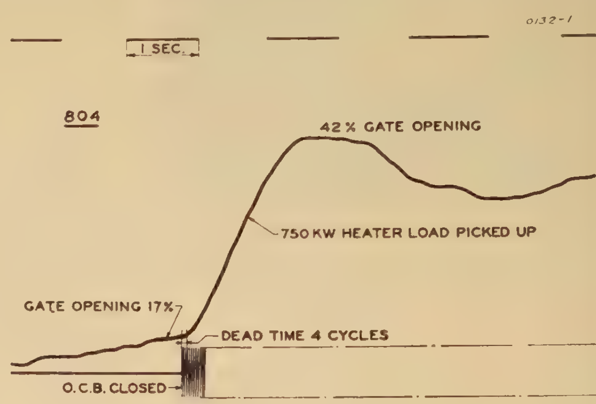


Figure 1. 750-kw load applied

(*g*). Ease of starting and stopping the turbine by remote control. This permits *complete* control of the unit by the switchboard operator.

(*h*). Ease of applying frequency and load control methods.

(*i*). By means of simple test equipment, the sensitivity of the control element (frequency meter) of an electrical governor can be checked. A corresponding check of a fly-ball device is more difficult and complicated.

The writer is of the opinion that a description of the device and an account of the progress made up to the present, may prove of interest to engineers in general, and more particularly to those who are intimately concerned with governing problems.

Paper 40-132, recommended by the AIEE committee on power generation, and presented at the AIEE Pacific Coast convention, Los Angeles, Calif., August 27–30, 1940. Manuscript submitted April 2, 1938; made available for preprinting July 15, 1940.

FRANK I. MORGAN is maintenance engineer, Pennsylvania Water and Power Company, Baltimore, Md.

---

2 and 3 and has an over-all length of $12^1/_2$ inches. Here the initial rush of current reaches a maximum value of only 400 amperes, whereas the surge voltage is limited to 23 kv. Figure 8 shows a cathode-ray oscillogram of the voltage surge at the time of current limitation for the same test.

Summary

1. A new type of current-limiting fuse has been developed and tested.

2. The construction of the fuse is such that the voltage surge as well as the current surge during interruption is limited to definite and predetermined values.

3. Tests on high-capacity systems have not revealed the limitations of the fuse. Indications are that the fuse has an exceedingly high interrupting ability.

4. The design of the fuse is flexible. Time-current characteristics can be obtained as desired.

5. The fuses may be applied to the protection of potential transformers and other apparatus of small power consumption. They are especially applicable to use in enclosed switchgear.

Bibliography

1. HOCHSPANNUNGS-HOCHLEISTUNGER TRENNSICHERUNGEN, *E.T.Z.*, August 27, 1931, page 1122.

2. THE BORIC-ACID FUSE, A. P. Strom and H. L. Rawlins. AIEE TRANSACTIONS, volume 51, p. 1020.

3. THE EXPULSION FUSE, J. Slepian and C. L. Denault. AIEE TRANSACTIONS, volume 51, 1932, page 157.

4. THE CURRENT-LIMITING POWER FUSE, D. C. Prince and E. A. Williams, Jr. AIEE TRANSACTIONS, volume 58, 1939, pages 11–14.

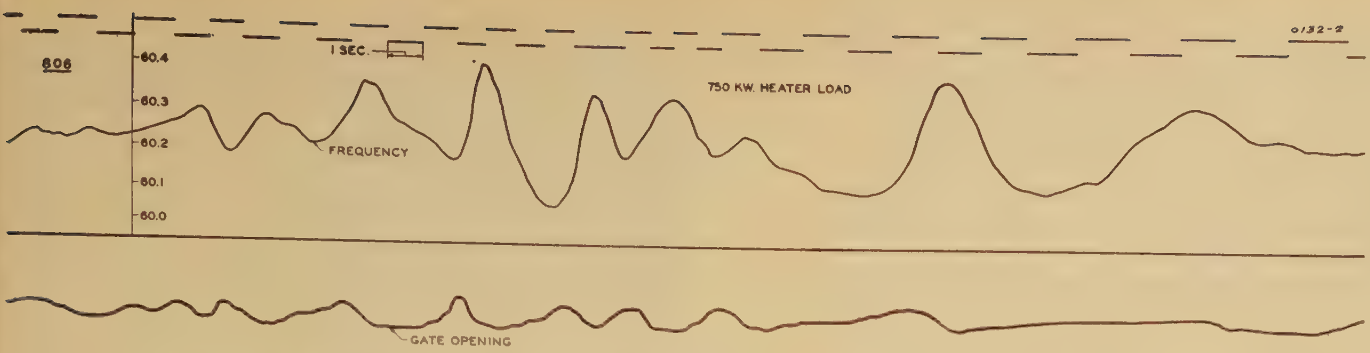


Figure 2. Frequency-gate movement

Preliminary Tests

The three tracings of oscillograms shown are a record of the performance of the governor during preliminary tests made in January and May 1937. These records are submitted, not as an indication of what can ultimately be accomplished, but simply to show the progress made up to the time of these tests.

The load on the unit during these tests was a purely resistance one amounting to 750 kw and it was possible to throw it on and off the unit at will.

Figure 1 (oscillogram number 804) shows the operation of the governor when a load of 750 kw was suddenly thrown on the unit. The governor started to open the gates in the remarkably short time of 4 cycles (60-cycle basis).

Figure 2 (oscillogram number 806) shows frequency and gate opening variations while the unit was carrying the load mentioned above.

Figure 3 (oscillogram number 808) gives the result of dropping load tests, showing the action of the governor when the load of 750 kw was dropped by opening the generator circuit breaker. The time required for the governor to start closing the gates varied from six to nine cycles.

Subsequent to the tests described in the foregoing, the apparatus has been applied to a double runner 13,500-horsepower turbine. This unit is equipped with a standard fly-ball governor of an old design. The control of its pilot valve was transferred from the flyballs to the electrical governor. The speed regulation, after the change, was very satisfactory and far superior to that obtained with the flyballs in control.

Operating Principle

An instrument sensitive to frequency variations and having two parallel electrical circuits, one branch containing resistance and the other reactance, is used as the control element. The change in impedance of the reactance with frequency is balanced by a corresponding change in resistance so that the currents flowing in the two branches of the circuit are maintained equal in value. The required changes in resistance are obtained by means of variable rheostats. Being a "null" method, the action of the control element is unaffected by changes in voltage within wide limits.

Referring to the schematic diagram, figure 4, *A* is a Kelvin balance employed as the frequency-responsive element, the moving coils of which are provided with a contact 27. This contact engages with either of the stationary contacts, 28 or 29. A resistance 10, is connected to one set of coils 3, and a reactance 11, to the other set of coils 2, of the Kelvin balance. Solenoids 24 and 25 actuate the walking beam 22, to which is connected the valve 18, admitting pressure fluid to either end of the "servomotor" cylinder 1. Rheostats 12 and 13 provide "compensation", the movable contact of rheostat 12 being connected to the servomotor piston rod by lever 30. The movable contact of rheostat 13 is connected to lever 30 by rod 33 and springs 31. A dashpot is provided to delay the movement of the contact of rheostat 13.

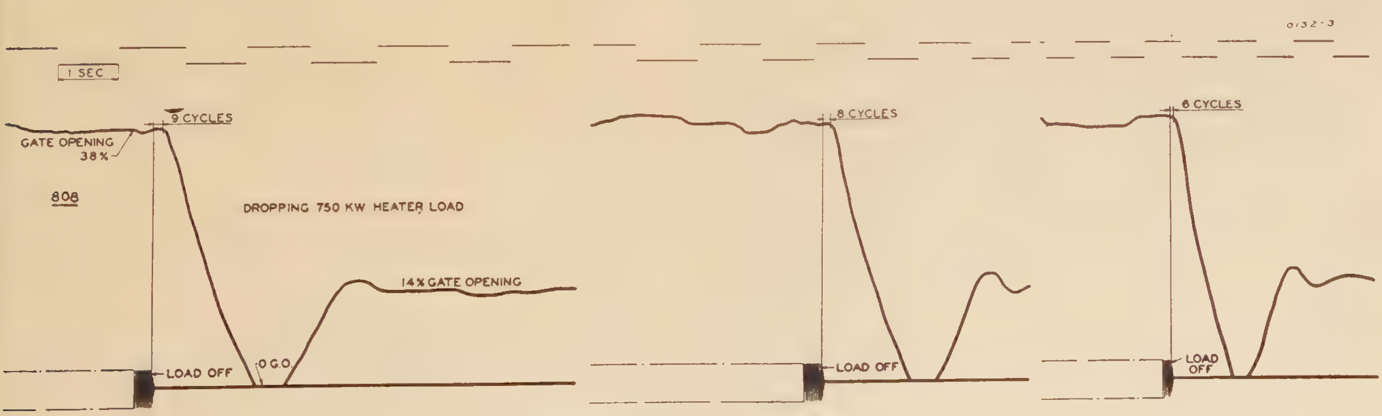
"Inherent speed drop" (also called "degree of irregularity," or the decrease in speed between no load and full load necessary for parallel operation) is adjusted by changing the location of the pivot point of rod 33 on the lever of rheostat 13.

The speed maintained by the governor is adjusted by means of rheostat 14.

Operation

Assuming normal frequency and steady load conditions, the currents flowing through the two sets of coils of the Kelvin balance are equal and the moving coils are in equilibrium, contact 27 being midway between contacts 28 and 29. Now, if the load on the unit increases, the speed will drop, lowering the frequency. Because of the lowered frequency, the reactance of 11 is decreased permitting more current to flow through coils 2 of the balance, upsetting the equilibrium of the moving coils. Contacts 27 and 29 close, energizing solenoid 24 which moves walking beam 22 and valve 18. Pressure

Figure 3. Dropping load tests



fluid then flows through pipes 20 and 21 to the servomotor, the piston of which moves to open the wicket gates of the turbine.

The movement of the walking beam 22, by the solenoid 24, also increases the resistance of rheostat 15 sufficiently to reduce the current in coils 2, to normal, restoring the equilibrium of the Kelvin balance moving coils and separating contacts 27 and 29.

The opening of the wicket gates by the servomotor increases the resistance of rheostat 12 by moving lever 30. This additional increase of resistance in series with coils 2 unbalances the moving coils in the opposite direction, closing contacts 27 and 28 to energize solenoid 25, which moves walking beam 22. This results in return of valve 18 toward its neutral position, and at the same time, decreases the resistance of rheostat 15. It should be noted that the movement of valve 18 back to its neutral position is simultaneous with the opening of the gates by the servomotor and the increase in resistance of rheostat 12.

When the resistance of rheostat 12 has been increased by an amount equivalent to the decrease in impedance of reactance 11 and the increase in resistance of rheostat 15 by the initial movement of the walking beam, the equilibrium of the Kelvin balance is again restored and valve 18 has been brought back to its neutral position, stopping movement of the gates.

The wicket gates have now been opened to increase the amount of water to the turbine, but because of the inertia of the water, its flow does not immediately increase. During the time the gates are being opened to the new load position and until the flow of the water increases sufficiently, the additional load demand is met by energy stored in the revolving parts of the turbine and generator which is released by a decrease in speed. As the flow of water increases through the greater gate opening, the speed of the unit returns toward normal. Unless provision is made to prevent it, this increase in speed (and frequency) toward normal would upset the equilibrium of the Kelvin balance—which has been balanced for the lowered speed of the unit by the change in resistance of rheostat 12—and cause a closing movement of the gates. This is avoided through the action of springs 31, rheostat 13, and the dashpot. (Second compensation.)

The tension of the spring 31 has been increased by the movement of lever 30, and the contact of rheostat 13 moves slowly, because of the restraining action of the dashpot, to reduce its resistance. Provided the setting of the dashpot bypass is correct, the resistance of rheostat 13 will decrease at the same rate as the speed (and frequency) increases to normal value, the equilibrium of the Kelvin balance will not be disturbed and, when movement of rheostat 13 ceases, the unit will be again running at normal speed, although the load has been increased. Circuit conditions of the governor (assuming isochronous adjustment) will then be exactly as they were before the change of load occurred.

It is apparent that increasing the resistance of rheostat 14, has the same effect as an increase in impedance, of reactor 11, resulting from an increase in speed (and frequency) of the turbine. Such an increase of resistance will cause the governor to close the turbine gates by a definite amount and lower the turbine speed.

Conversely, a decrease in resistance of rheostat 14 will cause the governor to open the turbine gates and increase the speed of the turbine.

The action of the governor on a decrease in load is, practically, the reverse of that described in the foregoing.

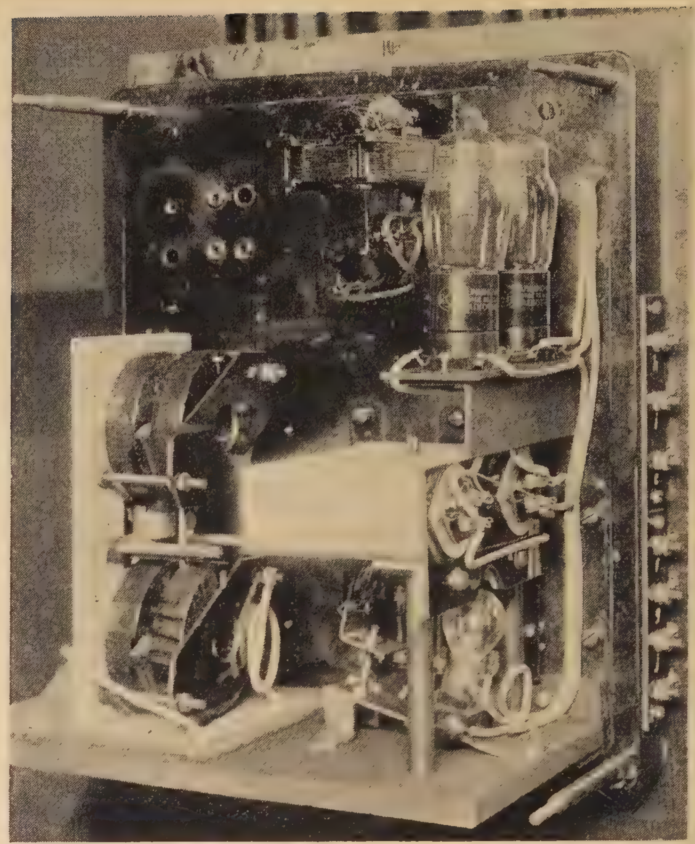


Figure 5. Magnetic vane instrument

Control Instrument

A Kelvin balance is entirely satisfactory as far as sensitivity is concerned but it was found that the moving coils possessed too much inertia to give the necessary speed of response, even when made of minimum weight and mounted in jeweled bearings. The contact system was unsatisfactory because the vibration inherent in such an instrument when used with alternating current had the effect of greatly increasing the contact resistance. Many different forms of contact mounting were tried but none was found entirely reliable.

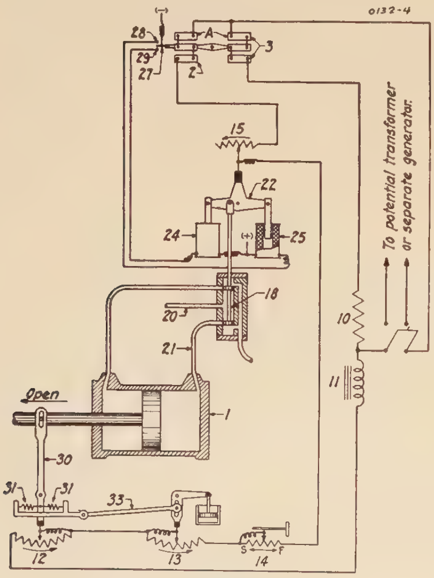


Figure 4. Schematic diagram

A magnetic vane instrument, shown in figure 5, was constructed and substituted for the Kelvin balance. The moving element of this instrument consists of a small aluminum shaft fitted with steel pivots, on which two light annealed steel vanes are mounted. This shaft is supported in jeweled bearings. Each vane is surrounded by a coil, one of which is connected in series with resistance 10, the other being connected in series with reactance 11. The vanes are placed on the shaft at an angle of approximately 80 degrees with respect to one another so that, with current flowing through the two coils, they tend to move in opposite directions and the shaft assumes a position depending on the relative strengths of the currents in the two coils. The moving element is dampened by a small oil dashpot. A small mirror is mounted on the shaft midway between the ends.

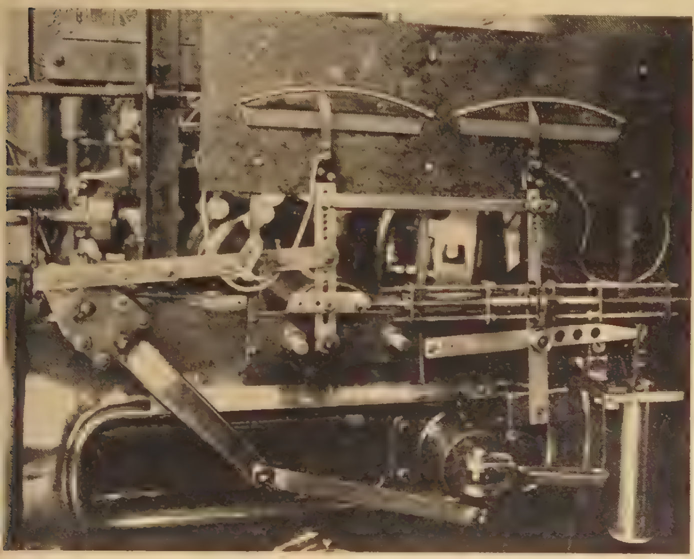


Figure 6. Compensation rheostats

Light from a 21 candle-power automobile head lamp is reflected from the mirror to two photoelectric cells which are connected to the grids of two vacuum tubes. The two coils of a differential relay of the D'Arsonval type are connected in the plate circuits of the tubes. The contacts of this relay control the solenoids 24 and 25 which operate valve 18.

The use of a lamp and vacuum tubes naturally raises the question of reliability since that feature is of paramount importance in a governor.

Records of lamp life, in continuous telemeter service, have shown that the life of such lamps (6–8 volts) when operated at 4 volts, varied from 12,000 to 19,000 hours.

An effective means of insuring reliability is the use of a double filament lamp (number 2331) and two sets of vacuum tubes. A simple one-contact relay operates to connect the second set of tubes and the second lamp filament in the event any one filament fails in the first set. If desired an alarm contact could be added to the relay.

Power Requirements

The magnetic vane instrument requires about 30 volt-amperes for its operation including the 21 candle-power lamp and the filaments of the vacuum tubes. This indicates that the load on a potential transformer for this type of governor would be quite negligible and makes feasible the use of a small magneto for this purpose if it were considered undesirable, from the standpoint of reliability, to use potential transformers.

Governor Action on Loss of Load

When a heavy load is suddenly dropped from a hydraulic turbine, the speed immediately increases and the governor promptly closes the gates. Because that part of the compensation device (second compensation) which contains the time delay feature acts slowly, the speed reaches its highest value and decreases toward normal before the time delay element has returned to the point where it can function properly for the gate opening required to maintain normal no-load speed. As a result, when the speed decreases sufficiently to cause the flyballs to start opening the gates, the second compensation cannot operate properly and the gates are opened far beyond the point necessary to maintain normal speed at no load. The turbine overspeeds, causing the flyballs to again close the gates completely. During each interval of gate closure, the second compensation approaches the position where it can function properly. Until it reaches this point, these gate opening and closing cycles repeat at intervals with gradually decreasing amplitude. The effect, for the time being, is much the same as that which would be obtained if the second compensation feature were omitted.

This objectionable operation has been remedied in one well-known make of governor by means of a cam which increases the action of the spring which opposes the centrifugal force of the flyballs. This cam begins to be effective when the gates, on closing, reach the point which admits sufficient water to operate the turbine at about normal speed with no load. The cam increases the "regulation" of the governor at no load, i.e., it adjusts the flyballs so that the speed maintained at no load is considerably higher than that at full load. In other words, the cam provides additional compensation for a limited range of gate movement. In this way, as the turbine

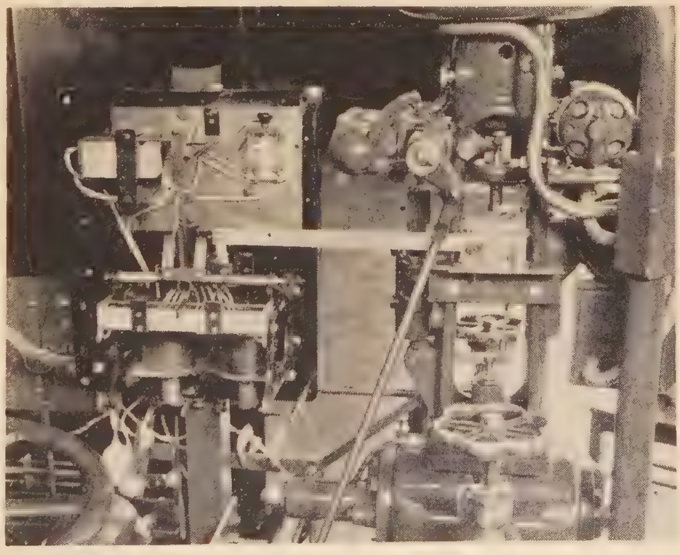


Figure 7. Pilot-valve solenoids

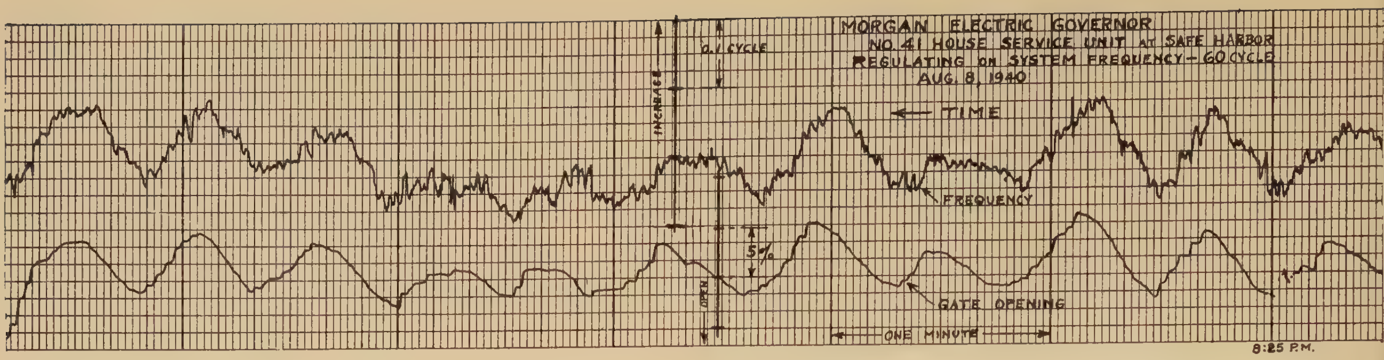


Figure 8. Record of test made August 8, 1940

slows down, the flyballs start to open the gates sooner than they would had no adjustment been made, the downward trend of the speed is arrested earlier and the second compensation functions properly. In addition, the opening movement of the gate is stopped at a point at which the readjusted speed will be maintained.

In at least two other makes of governors, this surging of gate movement and speed after dropping heavy loads is avoided by the provision of a bypass for the dashpot, which is opened automatically when quick gate movements beyond a certain amount occur.

In the governor described above, a bar is used to connect the movable levers of the compensation rheostats 12 and 13. This bar is slotted at the end connected to the lever of rheostat 13, as can be seen in figure 6. The purpose of this bar is the return of the lever of rheostat 13, on large, quick gate movements to a point where the second compensation can function properly. The slot allows the second compensation to operate normally on small gate movements or large gate movements which do not take place rapidly. This method of overcoming the faulty operation mentioned above has the advantage that no change is made in the regulation of the governor.

Load Limit and Safety Devices

Limitation of the load carried by the unit can be accomplished by arranging a stop, operated by an electromagnet, to prevent movement of walking beam 22 and valve 18 to cause further opening of the gates. The electromagnet would be energized through suitably arranged contacts to be closed by lever 30, these contacts to be adjustable so that the gate opening could be limited to any degree desired. This arrangement would not interfere with the closing of the gates at any time.

Emergency shutdown of the unit could be accomplished by the use of a relay, which when de-energized, would release a spring to move the pilot valve, independently of solenoids 24 and 25, in the direction to close the turbine gates. The relay releasing the spring could be operated by over-speed, over or undervoltage, decrease in governor fluid pressure below a definite value, etc.

Conclusion

No claim is made that the method of governing described in the foregoing is the ultimate solution of the problem of regulating the speed of hydraulic turbines. It is readily apparent that the results obtained, so far, with this experimental set-up, are more or less academic in value, and that the real worth of the method can only be determined by considerable operating experience which will bring out the weak points and emphasize those which are of advantage.

One possibility which may be deserving of consideration is the ease with which this equipment can be applied to obsolete or antiquated pressure operated governors and thereby secure the sensitivity and satisfactory operation of a modern governor without the expense of replacing the entire installation.

A High-Power Oilless Circuit Interrupter Using Water

W. M. LEEDS
MEMBER AIEE

THE oil circuit breaker has been for many years the standard type of circuit interrupter for heavy-duty powerhouse service. Since the introduction of modern arc-rupturing devices into these circuit breakers, the occurrence of serious trouble attributable directly to oil switchgear failure has been rare. However, the appearance on the market of various types of oilless circuit breakers of considerable interrupting capacity has encouraged the idea that the complete elimination of oil in power house switchgear may be both desirable and practicable. Further experimental investigation and development activity on the part of switchgear manufacturers seems to indicate that currents of 60,000 amperes or more at 13,200 volts can be interrupted satisfactorily in circuit breakers using either air or water as the arc-quenching medium. This paper describes the construction and operating characteristics of a high-power water circuit breaker.

Water Circuit Breakers

Interrupters using water as the extinguishing medium have a history of some 15 years, and are now used fairly extensively in moderate interrupting capacities, particularly in Germany.[1] In the form designated as "expansion breaker", the arc is drawn in a confined chamber where the generation of steam and gas quickly builds up a high pressure. The chamber is usually constructed of one or more sections resiliently mounted so that passages to a condensing chamber are opened up by the pressure, as indicated in figure 1. It is claimed that the deionization of the arc space is greatly accelerated by the cooling effect accompanying the sudden expansion of the steam. In any case, it is certain that the arc is subjected to a turbulent blast of steam and gas as these arc products make their escape laterally or longitudinally from the recesses in the interrupting chamber. The combined effect of cooling and turbulence causes dielectric strength to be built up with sufficient rapidity that the arc will not restrike.

Since even distilled water is a relatively poor dielectric the moving contact must be lifted clear of the water, and in many designs moved completely out of the chamber so as to interpose a series air break. The condensation of a large proportion of the vapors considerably reduces the external demonstration as compared with an oil breaker, the operation being somewhat quieter than an air switch. Factors which prevent this device from fulfilling the requirements of an ideal breaker include contamination and loss of water, and the possibility of corrosion of metal parts and deterioration of the insulation exposed to water or steam. Nevertheless, these problems are not at all insuperable, and high-capacity water breakers of the type described have been made experimentally for ratings up to 1,500,000 kva at 15 kv.

Water-Breaker Construction

Investigations on the breakdown of water under electric stress, by J. Slepian, C. L. Denault, and A. P. Strom,[2] indicate the desirability of not only removing voltage completely from the interrupting chamber immediately after opening the circuit, but also closing the circuit by an air switch rather than in the water. The experimental water-breaker pole unit shown in figure 2 is arranged with a series disconnect switch and also a main paralleling switch for continuous-current-carrying ratings of 1,200 amperes and above. The pole-unit mechanism is arranged to give the following sequence of operation:

Closing

1. Arcing contacts close in water.
2. Series disconnect switch completes the circuit in air.
3. Main switch closes, paralleling the arcing contacts and disconnect switch.

Opening

1. Main switch opens, diverting the current through the arcing contacts.
2. Arcing contacts open, extinguishing the arc in the water chamber.
3. Series disconnect switch opens, removing potential from the interrupter.

The different positions of the breaker contacts are illustrated in figure 3.

Although condensation reduces the amount of gas vented to the outside of the breaker, heavy local pressure impulses created in the neighborhood of the arc, when interrupting very high currents require exceptionally strong construction of the main body of the interrupter. Figure 4 is a cross section of the interrupting chamber. Overlapping inside and outside bronze cylinders *A* hold a heavy insulating tube *B* in compression and shear to develop maximum strength. Special attention has been given to the problem of shock absorption by providing a large air volume above the water level and also by utilizing the compressibility of air pockets sealed in rubber *C* located in the removable bottom bronze bell cover *D*.

The stationary arcing contact assembly consists of a cluster of fingers *E* while the arcing contact itself is made of a strong rustproof alloy rod *F* with a tip of arc-resisting material. This contact moves in and out of a chamber formed by three large blocks *G* of special insulating material with a centrally located water trapping pocket in each. A hollow spacer *H* above these blocks engages a rubber ring *I*. Pressure under the lowest block raises the whole arcing chamber assembly, compressing this rubber ring and at the same time opening the vent *J*.

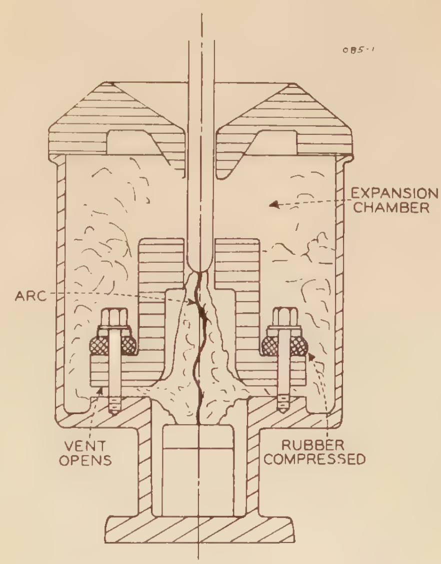


Figure 1. Siemens expansion breaker for low voltage

Paper 40-85, recommended by the AIEE committee on protective devices, and presented at the AIEE summer convention, Swampscott, Mass., June 24–28, 1940. Manuscript submitted November 13, 1939; made available for preprinting April 23, 1940.

W. M. LEEDS is electrical engineer in the switchgear engineering department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Among those of the author's associates who have aided in the development of this water breaker he wishes to acknowledge particularly the contributions of A. J. A. Peterson and A. H. Bakken in creating a workable mechanical design and the untiring efforts of B. P. Baker in following through the construction and testing of the experimental pole unit.

1. For all numbered references, see list at end of paper.

Table I. Interrupting Test on Experimental Water Breaker

13,200 Volts, Single Phase, 60 Cycles

Test	Current (RMS Amperes)	Interrupting Time (Cycles)	Arc Duration (Cycles)
Series A			
1	28,000	4.7	1.7
2	47,500	4.5	1.5
3	34,500	4.8	1.8
4	61,000	4.5	1.5
Series B			
1	9,100	4.3	1.4
2	7,500	4.3	1.5
3	25,000	4.4	1.6
4	27,500	4.4	1.6
5	27,500	4.3	1.5
6	26,000	4.2	1.4
7	51,000	3.9	1.2
8	29,000	4.2	1.4
9	44,000	4.3	1.4
10	35,000	4.6	1.7
11	58,000	4.2	1.3
Series C			
1	1,420	5.1	2.1
2	4,750	4.7	1.7
3	4,500	4.3	1.4
4	5,100	4.4	1.6
5	4,900	4.2	1.3
6	34,000	4.2	1.2
7	20,700	4.3	1.3
8	37,000	4.3	1.3
Series D			
1	50	4.2	1.3
2	50	3.8	0.9
3	150	3.2	0.3
4	150	3.5	0.6
5	290	4.5	1.6
6	295	4.5	1.6
7	620	4.4	1.5
8	600	4.5	1.6
9	910	4.2	1.3
10	810	3.7	0.8

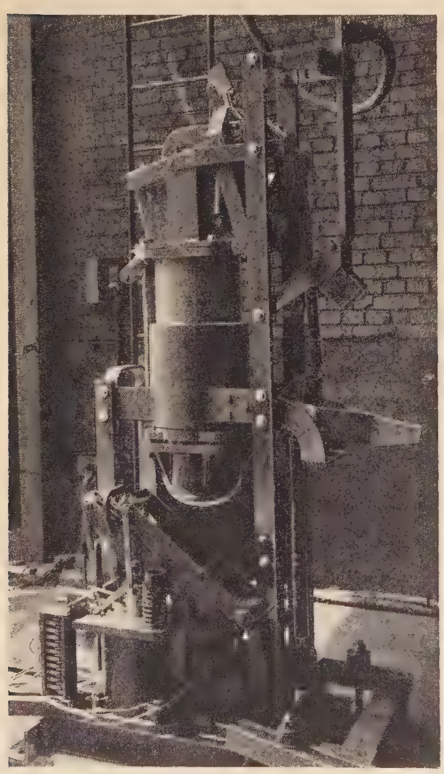


Figure 2. 15-kv water breaker experimental pole unit set up for interrupting tests

While research work by Kesselring and others in Germany might seem to have shown that arcs can be extinguished by the cooling action accompanying sudden expansion of saturated vapors surrounding an arc, it is not believed that this high-power water breaker operates in quite the same manner. For instance, no attempt is made to synchronize the opening of the vent and resultant vapor expansion with the instant of current zero. When interrupting a high-current arc, the vent *J* begins to open during the first half cycle of arcing. As the contact tip draws the arc *K* into each successive water pocket, more steam and dissociated gases are formed which turbulently mix into the arc stream

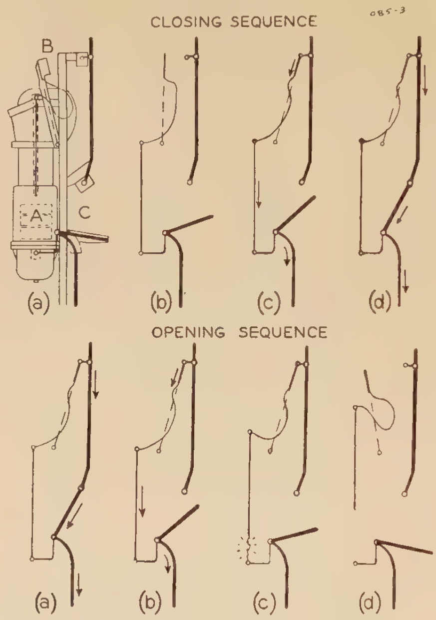


Figure 3. Switching sequence of water-breaker pole unit

A—Arcing break in water chamber
B—Series air disconnect
C—Main paralleling switch

Closing sequence:
(*a*) Open, (*b*) arcing contacts closed, (*c*) disconnect switch closed, (*d*) main contacts closed

Opening sequence:
(*a*) Closed, (*b*) main contacts opening, (*c*) arcing contacts opening, (*d*) disconnect switch open

on their way to the vent *J*. It should be noted further that the upward displacement of the interrupting elements *G* and *H* as the rubber ring *I* is compressed reduces the volume of the space between the upper block and the contact guide. This results in a quantity of water being forced in a longitudinal flow down along the contact and into the arc stream, tending to sweep the arc products downward and away from the contact tip. The de-

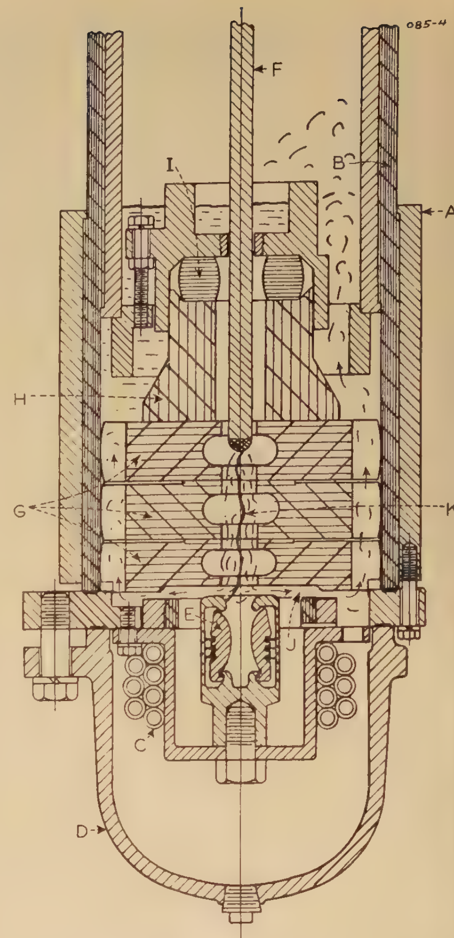


Figure 4. Cross section of interrupting chamber

A—Micarta tube
B—Bronze cylinders
C—Air-filled rubber
D—Bottom bell cover
E—Finger contacts
F—Arcing contact rod
G—Micarta blocks
H—Hollow spacer
I—Rubber ring
J—Arcing chamber vent

ionization produced by the turbulent flow of the relatively cool water vapor and steam through the arc space is so effective that at the first or second current zero after the arc is drawn into the bottom of the arcing chamber, the dielectric strength builds up with sufficient rapidity that reignition cannot take place and the arc is extinguished.

When interrupting lower currents the valve-type vent *J* opens only a very small amount, maintaining fairly high pressure in the arcing chamber. This keeps the gas bubble small, so that effective deionization is still obtained and the arcing time is only slightly longer than at high currents. By using only the one vent at the bottom instead of at several points along the arc stream all of the gas is

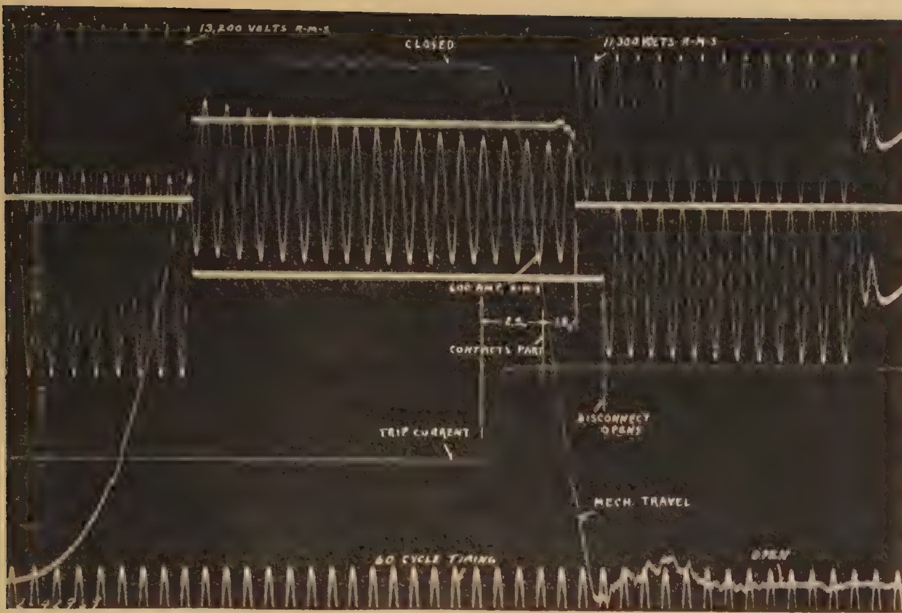


Figure 6. Oscillogram of low-current interruption at 13,200 volts

forced through the restricted arc passage and the deionizing action thus intensified.

The steam and gas from the vents are directed through a condensing labyrinth, shown in figure 5, and the permanent gases such as hydrogen and carbon monoxide that remain after the water vapor is removed pass out of a small port to the atmosphere. The amount of vented gas is estimated to be only about ten per cent of the total quantity generated by the arc, thus making possible almost complete enclosure of the interrupter. Water and steam that may be forced out around the upper contact guide is not thrown out of the breaker but only up into the mechanism chamber. Leakage from the chamber is avoided by providing a close-fitting bushing for the rotating shaft which operates the arcing and disconnect contacts.

Test Results

In table I are recorded a few of the results from the many series of interrupting tests on this water-breaker pole unit. A current range of 50 to 61,000 amperes at 13,200 volts is covered in these tests, the arcing time averaging close to $1^1/_2$ cycles for all currents. Oscillograms of representative opening and close-open interruptions are shown in figures 6, 7, 8, and 9. These show that for only the last one or two half-cycles of this time is there appreciable arc voltage, indicating effective action as soon as flow through the arcing chamber is established. The closing of high currents on the air-disconnect-switch contacts is accomplished with very little arcing due to the high-speed snap action. On the opening stroke, this switch shows a small spark when clearing the very low residual current conducted through the water in the arcing chamber immediately following the interruption of the main arc. The burning at the main contact and fingers is found to be very moderate considering the length of the current path through the arcing contact and disconnect switch to which the short-circuit current must be transferred by the opening of the main paralleling switch.

Distilled water is used in the breaker, samples from the interrupter usually measuring about 100,000 ohm-centimeters just after filling. The tests indicate that 100 or more low- and medium-current interruptions can be made before the resistivity will go to a value which indicates the need for water replacement. From four to six short circuits in the range from 40,000 to 60,000 amperes can be interrupted without changing the water in the breaker. The interrupting effectiveness of this water breaker design is clearly demonstrated by the fact that although the full operating line voltage was applied across a single-pole unit, the arc was quickly extinguished after separating the arcing contacts only a few inches in the single interrupting chamber.

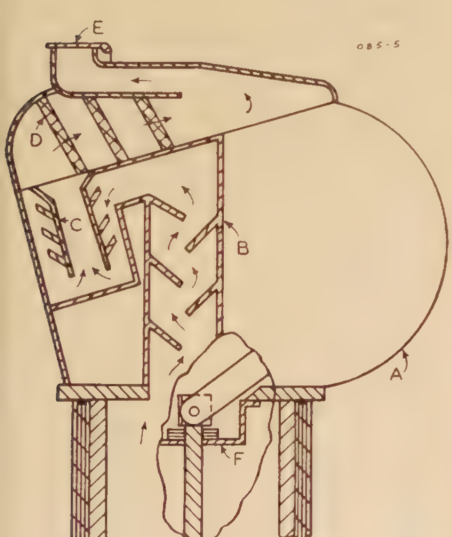
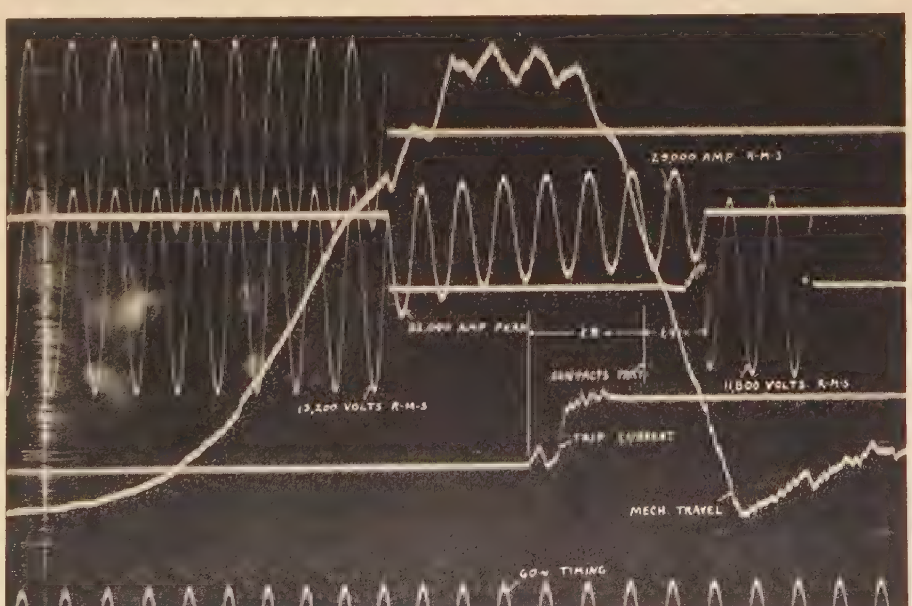


Figure 5. Steam condensing and venting channels

A—Mechanism chamber
B—Baffled passage beside mechanism chamber
C—Centrifugal separator
D—Metal screens
E—Hinged cover
F—Upper contact guide

Figure 7. Oscillogram of close-open test interrupting 29,000 amperes at 13,200 volts



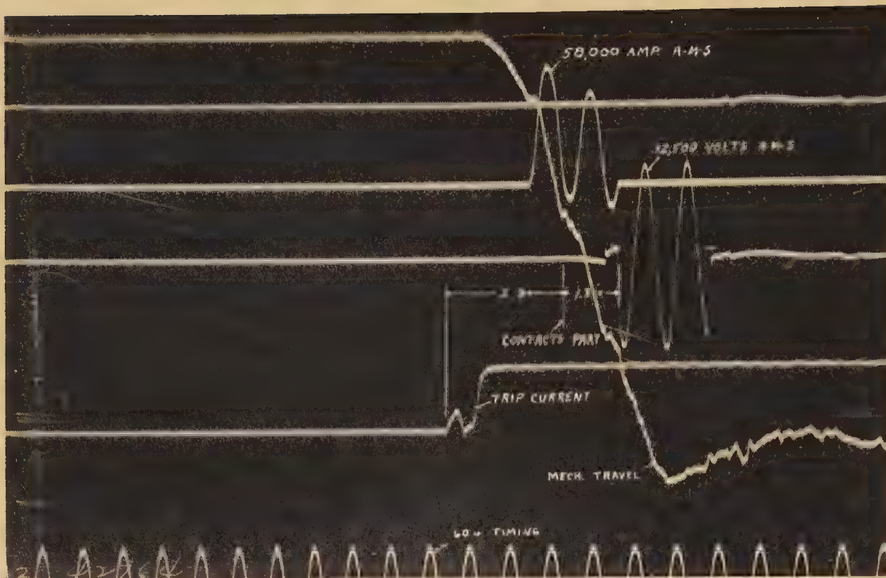
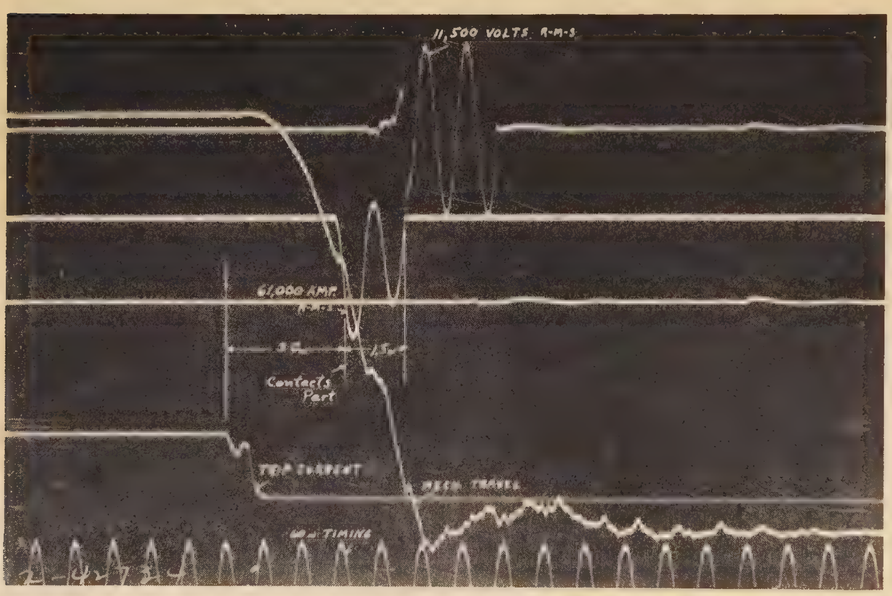


Figure 8 (above). Oscillogram of opening test interrupting 58,000 amperes at 13,200 volts

Figure 9 (below). Oscillogram of opening test interrupting 61,000 amperes at 13,200 volts



Advantageous Design Features

Features of particular interest in the design of the water breaker just described are as follows:

(*a*). The bottom bell *D*, figure 4, is readily removable for access to the stationary contact structure without disturbing the mounting of the pole unit.

(*b*). Because of the top enclosure of the pole unit, very little water or gas can escape into the surrounding air when the breaker is opening short circuits. The outlet for gas is designed to strain moisture from it before it reaches the atmosphere.

(*c*). No porcelain is used in the construction of this breaker.

(*d*). The main current-carrying loop being at the rear of the pole unit is of minimum length, and the severe mechanical strains caused by short-circuit currents which occur in many designs are not present in this one.

Conclusions

Tests on a high-power water breaker have shown that water can be used as an arc-extinguishing medium with results comparable to an oil circuit breaker. With proper precautions in the design which take into account the relatively low dielectric strength of water and the possibilities of corrosion, the water breaker becomes very interesting. As further experience is obtained it may find a place in the field of oilless switchgear for central-station service in America as it has in Europe.

Bibliography

1. The Expansion Breaker, **F. Kesselring.** *VDI*, volume 78, March 1934, pages 293–7.

2. The Dielectric Strength of Water in Relation to Use in Circuit Interrupters, **J. Slepian, C. L. Denault,** and **A. P. Strom.** AIEE Transactions. Volume 60, 1941.

Transactions Section

Preprint of Corresponding Pages From the Current Annual Transactions Volume

Any discussion of these papers will appear in the June 1941 "Supplement to Electrical Engineering—Transactions Section"

A Power-System Governor Sensitive to Frequency and Load

THOMAS E. CURTIS
ASSOCIATE AIEE

Synopsis: This paper describes a new electrical control system with which a standard power-system governor may be made sensitive to system load as well as frequency. A proposed scheme of application is presented which is believed to permit electrical control of a standard governor instead of mechanical control, without any sacrifice of reliability.

THE frequency of a power system is governed by controlling the power input to the prime movers of the system. Consider, for example, a typical power system in which one hydraulically-driven synchronous generator is governing the system frequency. Since the remaining generating units are operating at constant loads, the power output of the governing unit must be regulated so that the unit will assume any variations of load on the system. Simultaneously, this unit is controlled to hold the system frequency at a constant value.

Figure 1 is the schematic representation of a typical governing system of a hydro-electric generating unit. The power output of this unit is regulated by varying the opening of the needle valve to control the flow of water through the turbine This valve is operated by oil pressure through a control valve and piston, as shown in figure 2. The speed-sensitive element in this governing system is a centrifugal governor, driven from the turbine shaft, which operates the control valve by pivoting the beam about point P.

To meet changing system load, the load level of the governor is varied by the electrically-operated load control. The load control is operated through a contact-making frequency meter, connected to the system, which periodically resets the motor to change the relationship between the elevation of point P and the opening of the needle valve. The governor operation is thereby made isochronous.

It is now pointed out that the governing system just described is actuated by turbine speed and system frequency. A definite time lag must then exist in its operation to compensate for system load changes, since the rate of change of frequency which results from a differential between power generated and power demanded must exist for a definite period of time before frequency and turbine speed change sufficiently to actuate the governor. It is the purpose of this paper to describe a new governing system which is sensitive to both frequency and load.

Operating Principle

Figure 3 is a schematic representation of the proposed governing system. The turbine governor is actuated by an electronic frequency controller, through the medium of a balanced solenoid. This frequency controller provides two distinct components of control to make the governor sensitive to both frequency and load. The first component is derived from the pair of d-c currents I_A and I_B as functions of α, the rate of change of frequency in cycles per second per second. The second component is derived from the pair of d-c currents I_C and I_D as functions of F, the frequency in cycles per second. The controlling currents I_A, I_B, I_C, and I_D are obtained through the use of vacuum-tube circuits in the frequency controller. The characteristic operating curves are shown in figure 3. Current values are indicated in milliamperes. The solenoid plunger is then displaced from its central position in proportion to the current unbalance between I_A+I_C and I_B+I_D. An unbalance of I_A and I_B then actuates

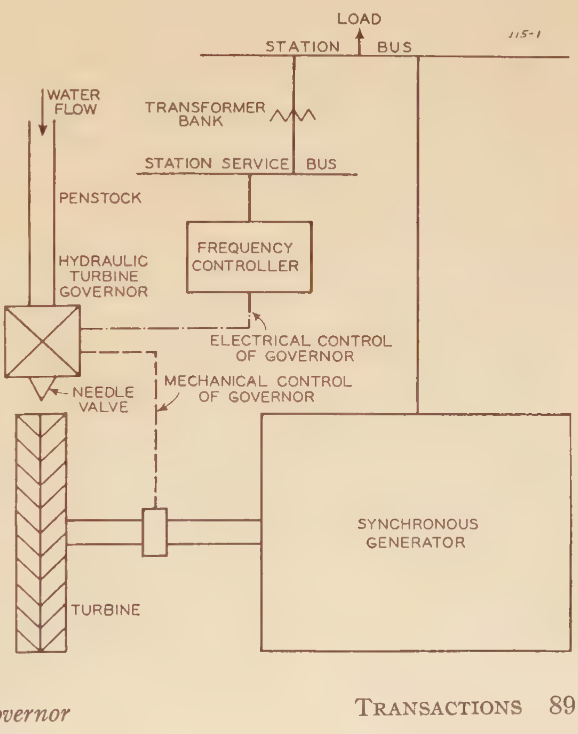


Figure 1. Governing schematic of hydroelectric generating unit

Paper 41-15, recommended by the AIEE committee on power generation and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941.

Manuscript submitted November 25, 1940; made available for preprinting November 28, 1940.

THOMAS E. CURTIS is electric underground estimator for the Pacific Gas and Electric Company, Oakland, Calif.

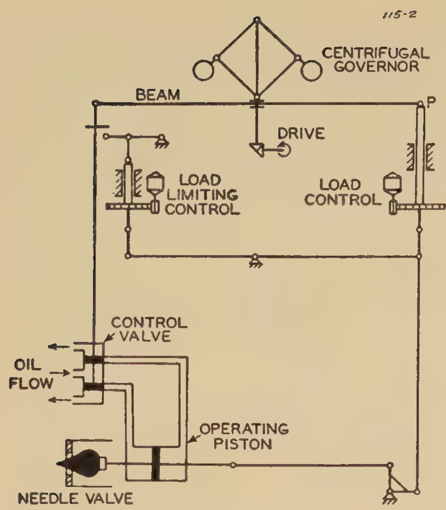


Figure 2. Hydraulic turbine governor schematic

the governor instantaneously whenever equilibrium is disturbed between power generated and power demanded. An unbalance of I_C and I_D actuates the governor whenever frequency deviates from its normal value.

The balanced solenoid operates the governor control valve through the conventional mechanical linkage, similar to that shown in figure 2. However, the standard centrifugal governor is retained on a separate beam. The controller beam and the governor beam have a common pivot at one end. At the other end, there is an interlocking pivot arrangement which couples to either one beam or the other. The solenoid M is energized to transfer *from* the governor beam *to* the controller beam. Signal lights S indicate which beam is in use. Four limit contacts are attached to the assembly of the interlocked pivots. One of these will make contact with whichever beam is uncoupled should any condition arise which disturbs their normally parallel operation. The limit contacts will then operate time-delay relays R_3 and R_4 to transfer control to the governor beam, or to prevent closing to the controller beam when conditions are not correct. The relays have a time delay in order to prevent their operation by the load-sensitive component of control during the course of normal operation.

Isochronous control is provided by the periodic polarized relay R_2, which operates the load-control motor through relay R_1. R_3 has auxiliary contacts which block the operation of R_1 to raise the load level when R_3 has tripped. Similarly, the tripping of R_4 blocks the operation of R_1 to lower the load level. These blocking circuits protect the governor from faulty operation of the load control. As indicated in figure 3, automatic time control may be coupled in at relay R_2.

Due to the use of balanced circuits throughout the frequency controller, it is possible to place a balance relay R_6 in the common-current return to terminal E. Any fault conditions within the controller will change the current in R_6, thereby tripping R_5 instantaneously to transfer control to the governor beam. By shorting out R_2, the tripping of R_5 also prevents possible erroneous operation of the load control. Control is automatically transferred to the controller beam when the current through R_6 returns to normal, provided that the transfer circuit has not been opened by either R_3 or R_4.

As outlined above, the control system is protected against faults within the controller by balance relay R_6. If, for any reason, R_6 should fail to operate, either R_3 or R_4 will transfer control to the governor beam. Relays R_3 and R_4 provide a continuous check of the calibration of the frequency controller against the centrifugal governor.

For the sake of simplicity, the load-limiting control is not indicated in figure 3. See figure 2.

The operation of the control system for a sudden increase of load is indicated in figure 4. The curve I_D-I_C represents frequency deviation, and curve I_B-I_A represents rate of change of frequency. The solenoid operation is represented by the sum of these two curves, $-I_A+I_B-I_C+I_D$. The shaded area A for time T represents the net improvement in control that this proposed control system provides over and above that of existing governing systems. The operation of the load-control motor is indicated at the bottom of the figure.

Solenoid Characteristics

In figure 5 are shown the operating characteristics of the balanced solenoid. The ordinates D represent the displacement of the plunger from its central position. The force-versus-displacement curves for each coil change with the frequency applied to the controller. Thus, for an applied frequency of 60.5 cycles per second, the force curves of the two coils intersect at P_5, whose ordinate is the displacement assumed by the plunger. When the frequency applied to the controller is 60 cycles, the force curves intersect at P_4, where the plunger displacement D is equal to zero.

If a differential force dF is applied to the plunger, it can move through a displacement D_2, as indicated. This differential force may represent either the threshold force of the valve linkage or a

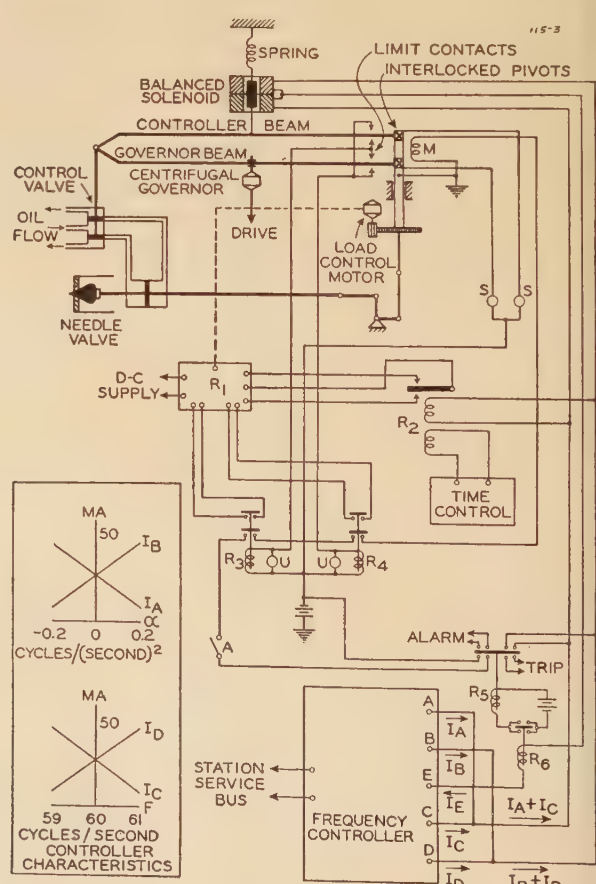


Figure 3. Proposed governing system

force tending to produce oscillation. In figure 6, which indicates the equilibrant forces of the centrifugal governor, it can be seen that the same differential force dF produces a relatively greater displacement D_1. Therefore, in comparing a centrifugal governor with a balanced solenoid operating in the same force range, the threshold limit of operation and the magnitude of possible oscillation of the solenoid is about one-half that of the former.

Curve A in figure 6 represents the restraining force of the centrifugal governor. The operating displacement is determined by its point of intersection with the lifting-force curve corresponding to the system frequency and turbine speed.

Controller Circuit

Figure 7 is the schematic circuit diagram of the frequency controller. System frequency is supplied to the controller through transformer T_1. A capacitance C_1 is connected in the circuit of one secondary winding, and an inductance L_1 is connected in the other. As frequency increases, the a-c current through R_1 decreases, while that through R_2 increases. The magnitudes of the a-c voltages appearing across R_1 and R_2 are converted into correspondingly proportional d-c currents in R_9 and R_{10}. This conversion is accomplished by vacuum tubes V_1, V_2, V_3, V_4, V_5, V_6, V_7, and V_8. Phase-shifting circuits C_2–R_3–C_3 and L_2–R_4–L_3 convert the single-phase voltage across R_1 to four-phase star voltages at the grids of tubes V_1, V_2, V_3, and V_4. Since the tubes are biased to cut-off, their action is that of rectification. The phase displacement of the plate-current pulses is such as to provide a nearly uniform current in R_9. Circuit C_6–L_6–C_7 filters out the remaining current ripple. The function of V_5, V_6, V_7, and V_8 is similar to that described above for V_1, V_2, V_3, and V_4, except that frequency response is inverse. Polyphase rectification is employed since it is essential that the d-c currents in R_9 and R_{10} should have a minimum ripple. Also, in order to minimize reactive transients, it is desirable to use polyphase rectification in order that circuits C_6–L_6–C_7 and C_8–L_7–C_9 may have a low reactance.

The d-c voltage across R_9 and R_{10} is a function of the frequency applied to T_1. This voltage is center-tapped by R_{11} and R_{12}, and applied to the grids of V_9 and V_{10}. The plate currents flow through two windings of transformer T_2 and R_{15} and R_{16}. The voltage across R_{15} and R_{16} is applied to V_{15} and V_{16} to provide currents I_C and I_D, as shown in figure 3.

A voltage appears across the secondary winding of T_2 when the plate currents of

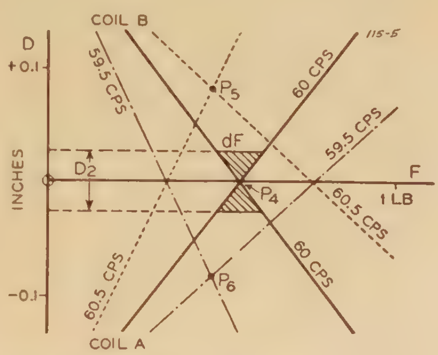


Figure 5. Equilibrant forces of balanced solenoid

V_9 and V_{10} are changing with respect to time. This voltage is therefore a function of the rate of change of system frequency with respect to time. It is amplified by V_{11} and V_{12}, and converted by V_{13} and V_{14} into currents I_A and I_B, also as in figure 3.

An alternative scheme for obtaining the load-sensitive component of control is the use of two capacitors and two re-

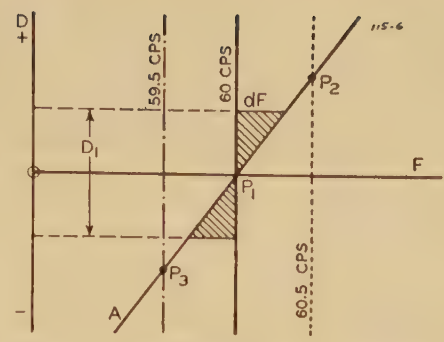


Figure 6. Equilibrant forces of centrifugal governor

sistors instead of the transformer T_2. This replacement of transformer T_2 is indicated in figure 8. A d-c current flows through R_{29} and R_{30} in response to a rate of change of potential across R_{15} and R_{16}. The voltage drop across R_{29} is then applied to the grid of V_{12}, while that across R_{30} is applied to V_{11}.

The response of the load-sensitive component of control is not strictly accurate when capacitors are used instead of the transformer. Thus, for a suddenly-applied frequency rate of change, the voltage response at the grid of V_{11} is:

$$e=k_1k_2R_{30}C+k_3R_{30}\epsilon^{-t/rC}$$

k_1 = time constant of applied rate of change of frequency
k_2 = voltage—frequency constant across R_{15} and R_{16}
k_3 = constant depending upon capacitor voltage conditions
C = series capacitance of C_{10} and C_{11}
$r=R_{29}+R_{30}$
t = time in seconds

It will be observed that the first term is directly proportional to the frequency rate of change. The second term is a capacitive transient during the initial period of the change while voltages are seeking their proper relationships. During tests, this transient was observed to be of the order of one-half second.

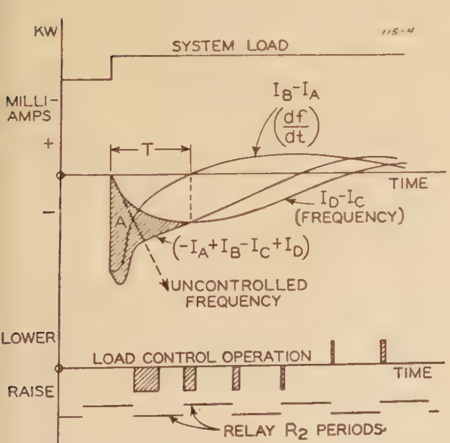
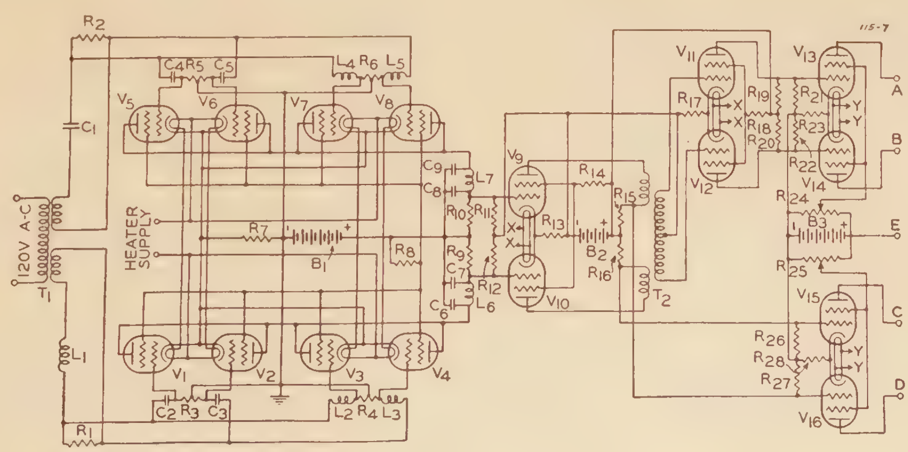


Figure 4. Operation of proposed governing system for abrupt load increase

Figure 7. Schematic of frequency controller



For a gradually varying rate of change of frequency, the response has one component proportional to and slightly lagging the rate of change, and one transient component similar to that of the abrupt rate of change.

The use of capacitors C_{10} and C_{11} eliminates the difficulty of core saturation of T_2 due to plate-current unbalance between V_9 and V_{10}. Operating experience may prove that the lagging and transient components present with the use of capacitors have no deleterious effect upon the quality of the frequency control.

The characteristics of the controller are readily variable. While maintaining the same normal current, the slopes of the I_A and I_B curves may be varied by adjusting R_{19} and R_{20}. Similarly, the slopes of the I_C and I_D curves may be varied with R_{15} and R_{16}. The current level of I_A and I_B is controlled by R_{24}. That of I_C and I_D is controlled by R_{25}. The normal operating points of the controller are independent of voltage variations at T_1. Supply-voltage variations affect only the slopes of the characteristic curves. The variation in slope is approximately proportional to the voltage variation. However, the effect of such variations is negligible.

Tests

The solenoid-operated control valve used in testing the frequency controller is shown in figure 9. The over-all length of this valve is seven inches. The operating piston, or servomotor, was operated by oil flowing through the two valve ports near the center of the valve. The component parts of the valve are shown in figure 10. This photograph shows the rear view of the brass valve cylinder. Oil under pressure was supplied to the center connection. Oil discharged from the operating piston passed through the outer two connections. The soft-steel valve plunger moves longitudinally through the two solenoid coils. The two center flanges match the valve ports shown in figure 9. Small diagonal holes were drilled through the flanges in order to revolve the plunger by the reaction of oil passing through. This rotation of the plunger maintained its freedom of movement. The two coils were connected to the frequency controller. Through the medium of the solenoid valve, the controller then controlled a piston-operated rheostat in the field circuit of a d-c shunt motor. This motor drove a 15-kva synchronous generator, from which the frequency controller was operated. The remaining two weeks of the allotted time in the laboratory did not permit perfection of the governor oil system. The simple oil-supply system available permitted the operation of the governor for less than a minute at a time. Under these conditions, it was not possible to complete adjustments of the control system. However, control of the motor-generator set by the frequency controller was established during these short intervals.

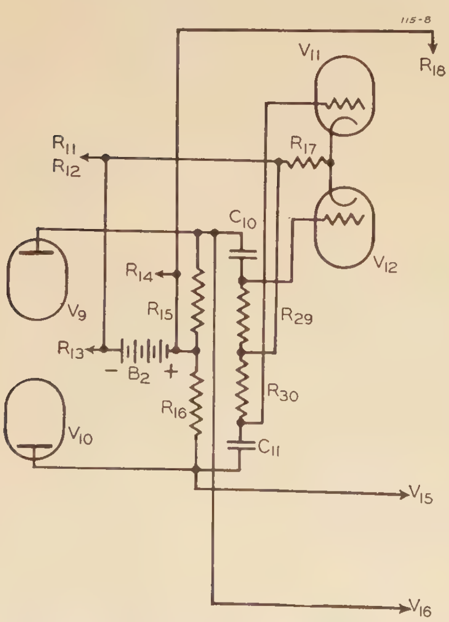


Figure 8. Alternative load-sensitive circuit for substitution in figure 7

Conclusions

A new electronic system of frequency control has been developed in the laboratory. It is believed that this control system can be adapted to standard hydraulic governors now in use.

The electronic frequency controller described in this paper provides movement of a solenoid plunger comparable to the controlling movement of a fly-ball governor. The controlling movement of a fly-ball governor depends upon change of speed. The controlling movement of the solenoid plunger depends upon both change of speed and rate of change of speed. It follows that a power-system governor controlled by such a solenoid should be sensitive to both frequency and changes in system load. A power-system governor controlled by a fly-ball governor is sensitive only to turbine speed.

The addition of the load-sensitive component of control eliminates one of the several time lags present in existing governing systems. The load-sensitive component of the solenoid motion actuates the governor to oppose hunting swings.

Figure 9. Solenoid-operated control valve used in tests

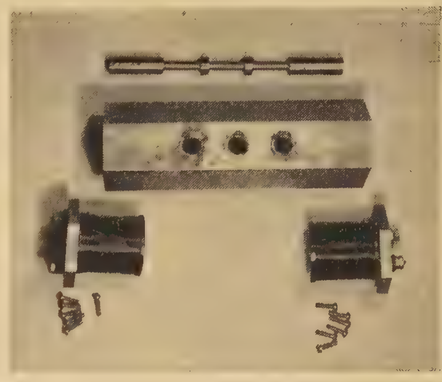


Figure 10. Component parts of control valve

It is believed that the solenoid described in this paper can be substituted, with no sacrifice of reliability, for the standard fly-ball governor head, provided that the latter is retained in a stand-by capacity.

The scheme of controlling machines in accordance with both speed and rate of change of speed is not new, as inertia governors have been used for many years in some applications other than electric power systems. It is believed, however, that the electronic control system herein proposed has the following advantages over the mechanical inertia governor:

(*a*). Response to rate of change of frequency separately adjustable during operation.

(*b*). Response to frequency deviation separately adjustable during operation.

(*c*). Increased sensitivity.

(*d*). Reduced oscillation of the governor.

(*e*). Several units may be governed at once by the one controller.

(*f*). Two or more controllers may be operated on the system at once, since adjustments may be made during operation to control load division.

(*g*). Two or more controllers on one system may be interlocked by pilot wires or carrier-current channels to control tie-line loads.

The essential operation of the controller and solenoid has been verified in the laboratory. It is hoped that the complete governing system proposed in this paper may be submitted to the test of operating experience in the near future.

Automatic Printing Ammeter

T. G. LE CLAIR
FELLOW AIEE

Synopsis: A new instrument has been developed which will automatically read and record in numerals, at predetermined time intervals, the ampere loading on 50 different electric circuits. This instrument also adds the readings on groups of circuits and prints these totals in columns beside the ampere load readings. The paper outlines briefly the reasons for developing such a device. The paper also describes, with the aid of schematic diagrams, the process by which the instrument obtains and prints all the measurements and totals on a single "log sheet."

Need for Compact Ammeter Records

THE rating of most electrical equipment is on an ampere basis. To determine when additional capacity in lines, transformers, or generators, is required on a power system, it is necessary to have an accurate record of past ammeter loads. For maximum usefulness, these ammeter records should be as compact and legible as possible for ready determination of the shape of the load curves and rate of growth.

In large power stations it is common practice for an operator to note and record on a "log sheet" the ammeter readings on all outgoing transmission lines at frequent intervals. When several of these outgoing lines supply the same load it is necessary to totalize the loads on all lines in a given group in order to estimate the load growth on the combined group. Figure 1 illustrates a typical group of substations fed by several lines from the same generating station. When 50 to 100 or more lines emanate from the same station the instrument readings must be recorded with a minimum of effort and in the most usable form. Recording instruments would be suitable for this purpose if their record could be compact enough.

Substations such as substation *A* in figure 1 may frequently be of an unattended type. In such a substation it is desirable to have ammeter records in convenient and compact form of the loading on transformers and distribution feeders. It is also desirable to obtain these records automatically, to avoid the expense of an attendant.

Paper 41-3, recommended by the AIEE committee on instruments and measurements and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted March 30, 1940; made available for preprinting October 26, 1940.

T. G. Le Clair is supervising development engineer for the Commonwealth Edison Company, Chicago, Ill.

The writer wishes to express his appreciation to Mr. H. M. Schaibly, whose quick perceptions and nimble fingers turned sketches and diagrams into a working machine. Appreciation is also due to Mr. J. R. Harrington and his associates for reducing the laboratory product to a flexible standardized design.

Available Types of Instruments

At present a number of types of instruments are available which can be used for obtaining compact records automatically. The most common type, of course, is the ordinary graphic instrument with one instrument installed on each circuit. These instruments are available with charts for various periods from one day up. There is also available a graphic instrument for ten circuits which, instead of drawing a load curve, puts on the graph paper a series of characters so that the line connecting the same characters is the equivalent of a graphic record. For totalizing the readings of several circuits, equipment is available by which either amperes or watts, a-c, can be converted to a d-c voltage, and the d-c voltages from several of these converters connected in series on a d-c instrument for a totalized reading.

In Chicago unattended substations the practice has been to use graphic instruments for ammeter records. In generating stations compact recordings of line readings are obtained by having an operator read a series of indicating instruments and record these readings on a log sheet in rows and columns. The usual arrangement is that each column represents the readings on a given circuit and each row is the series of readings taken at a given time. An increasing need was felt to relieve the operator of this burden in large stations, or to obtain these readings in substations where an operator is not on hand for 24 hours a day. This need resulted in the development of a measuring combination with the following basic principle:

Fundamental Principle of New Instrument

A single accurate measuring device is constructed which is automatically connected in turn to each of the circuits to be measured. The single measuring device is used in combination with a printer which records on a log sheet figures which are a measure of the magnitude of the current. The column position of a given reading on the log sheet signifies the circuit on which the reading was taken. The row position of the reading on the log sheet signifies the time when the reading was taken. The measuring device itself utilizes a balancing relay in which the current to be measured is balanced against the current from a standardizing source which is co-ordinated electrically to the printing device.

The totalizing of the readings is accomplished by means of additional mechanism which prints the total figures beside the readings which have been totalized. The new instrument eliminates the human error, both in the accuracy of the readings and in the timing of the periodic readings.

Laboratory Development

A simple experimental instrument was built first to show that the measuring principle would work. Later a full size model was made to record all the ammeter readings in one supervisory control substation. The complete model is shown in the photograph, figure 2. This model was constructed in the laboratory from various available standard parts. Recording is done on an ordinary typewriter on which the typewriter keys are operated by solenoids rather than by human fingers. The operating solenoids can be seen in the photograph directly under the typewriter keyboard at the top of the instrument cabinet. A sample of the record sheet obtained in this machine is

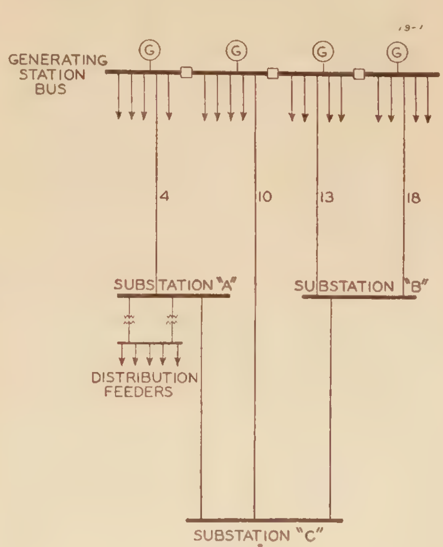


Figure 1. Typical transmission line group

The maximum loads on individual transmission lines may occur at different times due to different load characteristics on the three different substations

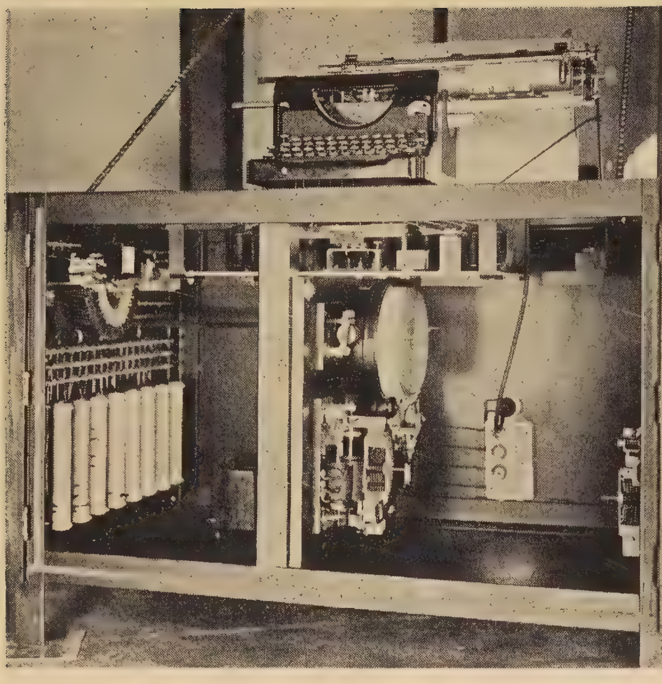


Figure 2. The first full-size automatic printing ammeter

This multicircuit printing ammeter, built in the laboratory, was the first one to record the loads on all transformers and outgoing 4,000-volt feeders of a complete substation

shown in figure 3. On this log sheet the first 12 columns of figures are the ammeter readings on each of the three phases of the four transformer banks. The remaining columns are the ammeter readings on the three phases of the outgoing 4,000 volt feeders. The spare circuit and circuit number 30 were not carrying load on the day this log sheet was taken. The figures on the log sheet are the ammeter readings in tens of amperes.

This machine, which has been in constant service for about three years, has given very satisfactory results and is adequate except for its home-made appearance. A detailed description of this printing ammeter and its method of operation will not be given in this paper because the principles are similar to those of the newer model which is appreciably more complete. The home-made instrument records the ammeter readings on 36 circuits and takes these readings every 30 minutes. At the end of the day, the log sheet for that day, in triplicate, is ejected from the machine automatically, and the log sheet for the following day is inserted ready for use.

Improved Design

After the laboratory model had been given a thorough trial in commercial operation, it was considered desirable to install a similar instrument in a generating

Figure 3. Typical log sheet from first full-size printing ammeter

This is a photograph of an actual log sheet showing the instrument readings on a typical day on all the circuits in an unattended substation

Daily Record of Ampere Loads on 4-Kv Circuits and Transformers

GOOSE ISLAND Substation Date 3/1/40

CIR. #	TR.#1			TR.#2			TR.#3			TR.#4			CIR.#43			CIR.#45			CIR.#41			CIR.#42			SPARE			CIR.#46			CIR.#3			CIR.#30		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
12:30	7	6	7	14	14	15	13	13	13	13	12	13	7	6	5	13	12	16	10	10	11	0	0	0	0	0	0	12	12	11	0	0	0	0	0	0
1:00	6	6	6	13	13	14	12	12	13	13	12	13	7	6	5	14	14	15	10	10	10	0	0	0	0	0	0	11	11	10	0	0	0	0	0	0
1:30	5	5	5	12	12	13	11	11	11	11	10	12	7	6	6	11	11	13	10	9	10	0	0	0	0	0	0	10	10	9	0	0	0	0	0	0
2:00	5	5	5	12	12	13	12	11	11	11	10	12	7	6	5	11	12	13	11	11	11	0	0	0	0	0	0	7	8	7	0	0	0	0	0	0
2:30	4	4	4	11	11	12	11	11	11	11	10	11	7	5	5	12	12	13	9	9	10	0	0	0	0	0	0	7	7	6	0	0	0	0	0	0
3:00	5	4	5	12	12	13	12	11	12	12	10	11	7	6	6	11	11	12	9	9	9	0	0	0	0	0	0	8	9	8	0	0	0	0	0	0
3:30	4	3	3	11	11	12	10	10	10	10	9	11	6	5	5	13	12	14	8	9	10	0	0	0	0	0	0	8	9	8	0	0	0	0	0	0
4:00	5	5	4	11	11	12	11	11	11	11	10	11	7	5	5	13	13	14	10	10	11	0	0	0	0	0	0	8	8	8	0	0	0	0	0	0
4:30	4	0	3	11	11	11	10	10	10	10	9	10	7	6	6	11	12	12	10	9	10	0	0	0	0	0	0	8	8	7	0	0	0	0	0	0
5:00	4	3	4	11	11	11	10	10	10	10	9	10	7	6	6	11	11	12	10	10	11	0	0	0	0	0	0	7	7	7	0	0	0	0	0	0
5:30	4	0	0	10	10	11	10	10	10	10	9	10	7	6	6	12	12	13	10	9	10	0	0	0	0	0	0	6	6	5	0	0	0	0	0	0
6:00	4	4	4	11	11	11	11	10	10	10	9	10	7	5	5	13	13	13	11	10	11	0	0	-0	0	0	0	6	6	6	0	0	0	0	0	0
6:30	4	4	3	11	11	11	11	10	10	11	10	11	8	6	6	11	11	14	10	10	11	0	0	0	0	0	0	8	7	6	0	0	0	0	0	0
7:00	5	4	5	12	12	12	11	10	11	11	10	11	8	7	7	10	10	12	12	11	12	0	0	0	0	0	0	9	9	8	0	0	0	0	0	0
7:30	10	9	9	18	17	18	17	16	17	17	15	17	8	8	8	12	11	13	12	13	13	0	0	0	0	0	0	22	21	19	9	7	8	0	0	0
8:00	11	10	11	19	19	20	19	18	19	19	17	19	11	10	10	14	12	14	15	15	15	0	0	0	0	0	0	22	21	20	9	7	8	0	0	0
8:30	19	18	18	31	31	33	30	28	30	29	27	29	15	14	14	20	19	22	24	26	25	11	11	11	0	0	0	27	27	24	13	12	13	0	0	0
9:00	20	19	20	33	32	34	31	30	32	31	29	32	18	17	16	23	22	24	28	30	29	11	10	10	0	0	0	27	27	24	13	12	13	0	0	0
9:30	19	18	19	32	32	33	31	29	31	30	28	30	18	17	16	21	19	22	27	29	29	12	11	10	0	0	0	25	25	22	11	10	11	0	0	0
10:00	19	18	19	32	32	33	31	29	30	30	28	30	17	18	17	21	21	22	28	28	28	10	10	9	0	0	0	28	27	24	11	10	11	0	0	0
10:30	20	19	20	33	34	35	32	31	32	31	29	31	19	18	17	23	21	25	30	30	30	10	9	9	0	0	0	25	26	23	12	11	12	0	0	0
11:00	20	18	19	33	32	34	31	30	32	31	29	32	18	18	17	23	22	25	29	29	30	11	10	10	0	0	0	27	26	23	12	10	12	0	0	0
11:30	20	19	20	33	33	36	32	31	33	31	29	33	18	18	16	22	22	24	30	31	31	10	10	11	0	0	0	27	26	24	12	10	12	0	0	0
12:00	17	16	17	29	28	30	27	25	27	26	24	27	15	15	14	20	19	22	25	25	25	7	6	5	0	0	0	23	22	20	11	9	11	0	0	0
12:30	10	9	10	18	17	19	18	16	18	17	16	17	12	11	11	20	17	18	17	17	18	5	0	0	0	0	0	15	14	13	0	0	0	0	0	0
1:00	18	17	18	31	31	33	30	28	30	29	27	30	16	16	15	21	20	23	28	29	29	11	10	9	0	0	0	23	23	20	11	10	12	0	0	0
1:30	19	18	19	31	31	33	30	29	31	29	28	30	16	15	15	22	22	24	28	29	29	10	11	10	0	0	0	24	22	20	11	10	11	0	0	0
2:00	18	17	19	31	30	32	30	28	30	29	26	30	17	16	15	20	19	23	30	29	30	9	9	9	0	0	0	22	22	20	12	10	12	0	0	0
2:30	18	17	18	30	29	32	28	28	29	28	27	29	18	18	16	22	21	22	28	29	30	11	11	10	0	0	0	21	21	18	12	10	12	0	0	0
3:00	17	16	17	29	28	30	28	26	28	26	25	28	16	15	15	21	20	23	27	27	26	12	10	9	0	0	0	20	20	17	11	9	11	0	0	0
3:30	16	15	16	27	28	29	26	25	27	26	24	27	16	14	15	21	21	22	24	25	25	12	10	10	0	0	0	17	17	15	10	8	10	0	0	0
4:00	15	14	14	25	25	26	24	23	24	24	22	24	14	14	13	20	19	21	23	23	23	10	10	10	0	0	0	14	14	12	10	9	10	0	0	0
4:30	12	11	12	21	21	23	19	19	20	19	18	20	12	10	10	19	18	20	17	16	16	7	8	6	0	0	0	11	12	10	8	6	8	0	0	0
5:00	10	9	9	17	17	18	16	15	17	16	15	16	11	10	10	21	16	19	14	15	15	6	5	4	0	0	0	10	11	9	0	0	0	0	0	0
5:30	10	9	9	18	17	19	17	16	17	16	15	17	11	9	10	19	18	20	14	14	15	5	4	0	0	0	0	10	10	8	0	0	4	0	0	0
6:00	9	8	9	17	16	18	17	15	17	17	15	16	12	9	9	19	17	21	13	13	14	5	3	0	0	0	0	10	11	9	0	0	3	0	0	0
6:30	9	8	9	17	16	18	17	15	16	16	14	16	11	8	8	19	17	20	13	12	13	4	4	4	0	0	0	10	10	8	0	0	0	0	0	0
7:00	9	8	8	17	16	17	16	15	16	16	13	15	10	8	8	20	17	20	12	12	12	4	4	0	0	0	0	9	10	8	0	0	0	0	0	0
7:30	8	7	8	15	14	16	15	13	15	15	13	15	11	8	8	19	15	19	12	12	12	5	4	0	0	0	0	9	9	8	0	0	0	0	0	0
8:00	9	8	9	17	16	18	16	15	16	15	13	16	11	8	8	20	18	21	12	11	12	6	4	0	0	0	0	9	9	8	0	0	0	0	0	0
8:30	8	7	8	16	15	16	15	14	14	14	13	14	10	7	7	17	15	19	12	12	13	0	0	0	0	0	0	9	9	7	0	0	0	0	0	0
9:00	8	7	7	15	14	15	14	13	14	15	13	15	10	7	7	20	18	21	11	11	12	3	0	0	0	0	0	9	9	7	0	0	0	0	0	0
9:30	8	7	8	15	14	16	15	13	14	14	13	14	9	7	7	18	15	18	12	12	12	0	0	0	0	0	0	8	9	7	0	0	0	0	0	0
10:00	8	7	7	15	14	15	14	13	14	14	12	14	9	7	7	18	16	19	12	11	12	0	0	0	0	0	0	8	9	8	0	0	0	0	0	0
10:30	8	6	7	15	14	15	14	13	14	14	12	14	8	6	6	16	14	17	11	11	12	0	0	0	0	0	0	11	11	9	0	0	0	0	0	0
11:00	7	6	7	14	13	14	14	13	13	14	12	13	8	7	6	16	15	17	11	10	11	0	0	0	0	0	0	10	10	9	0	0	0	0	0	0
11:30	7	6	6	14	13	14	13	12	13	13	12	13	8	6	6	16	15	17	11	10	11	0	0	0	0	0	0	11	10	9	0	0	0	0	0	0
12:00	7	6	6	14	13	14	13	12	13	13	11	12	7	6	6	14	14	16	10	9	10	0	0	0	0	0	0	10	10	8	0	0	0	0	0	0

Form E 269 5-28-37-S

station to record the ampere measurements on 45 outgoing transmission lines. However, in this station the indicating instruments are arranged in the same order on the switchboard as are the line switches on the busses in the station. The operator arranges the columns on his log sheet in the same order to avoid errors. Furthermore, the 45 lines are divided into ten different groups. The lines to a given group of load are not on adjacent switch positions, but are scattered throughout the station, as illustrated in figure 1, in order to diversify the supply to the load. This makes it necessary for the planning engineer, in using the log sheet, to look at scattered columns in order to totalize the loads in each group. Therefore, the design of the instrument was expanded to include a totalizing mechanism which records the total of the loads on the lines of each group in addition to the individual line loads.

The design was also increased in flexibility so that it would be a relatively simple matter to change the order in which the instrument readings appear on the log sheet or to change the groups of readings included in a given total. This was accomplished by the use of a plugging board arranged so that the secondary current circuits of transmission lines may be connected to the instrument in any order or grouping desired without changing any of the permanent wiring in the instrument. This is very convenient as new transmission lines are installed, or lines are cut over from one substation group to another, at intervals of a few months.

The new design also includes a printer which is designed as a part of the combined unit replacing the more cumbersome typewriter used in the early model. The result of this development is the instrument shown in the photograph, figure 4.

Parts of the Measuring Equipment

The measuring equipment in its finished form is shown in the photograph, figure 4. Figure 4*a* is a front view with the covers removed to show all of the operating parts of the equipment. Figure 4*b* is a rear view also with the cover removed, showing test switches. Each circuit to be measured is connected to a pair of these test switches, arranged so that the current circuit can be short-circuited and disconnected without disturbing any of the wiring within the instrument. The individual parts of the unit can be identified by reference to figure 5 which shows each element identified by name in the same physical position which it occupies in the photograph, figure 4*a*. For ease in describing the parts in the following method of operation, it is assumed that the current transformer ratios are 1:1 and that the instrument has a full scale reading of 100 amperes.

A contact-making clock is used to start the sequence of operations to obtain readings. This contact-making clock may be either a simple device making contact every 15, 30, or 60 minutes, or it may be set up with a definite program to take readings at variable intervals.

The master sequence switch is a rotary control switch used to determine the order in which the various functions of the instrument are performed. Each step in the process of taking measurements is controlled by this master sequence switch.

The circuit selector switch is a 50-point rotary switch with each of the circuits which are to be measured connected to one of the points or positions. A common connection leads from this switch to the measuring part of the equipment. Each circuit to be measured is normally short-circuited on itself in this selector switch but not connected to any other circuit. The circuit selector switch is used to connect each circuit in turn to the remainder of the equipment.

The balancing relay has two cores pulling at opposite ends of a balancing beam. The coil on one core is connected in turn to each circuit to be measured through the circuit selector switch; the current in this element is the current flowing in the measured circuit. The other core has two coils; each of these coils is supplied a variable current which is adjusted until the relay comes to a balance.

The measuring transformer is connected to a constant voltage a-c source and has two secondary windings to supply current to the two coils on the one core of the balancing relay through measuring switches.

The tens measuring switch is a rotary switch used to select steps on a resistor in the circuit from the measuring transformer to one coil of the balancing relay. Each step taken by this measuring switch increases the current in one coil of the balancing relay by ten amperes. Separate contacts on this measuring switch are connected to corresponding solenoid stops in the printing mechanism to select figures corresponding to the tens of amperes in the circuit.

The units measuring switch is similar to the tens measuring switch except that each step that this rotary switch takes varies the current in its corresponding coil of the balancing relay by one ampere instead of ten amperes. Separate con-

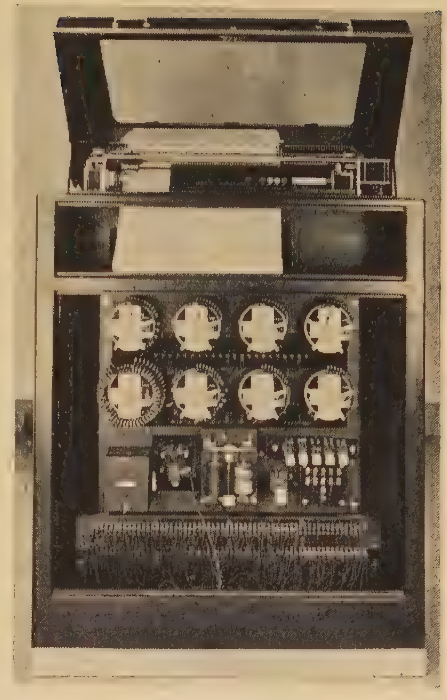


Figure 4a. Front view of standard model automatic printing ammeter

Covers have been removed to show mechanism. Printed forms feed from the front compartment through the printer mechanism at top. The typed figures on the log sheet are continuously visible through the glass cover when operating

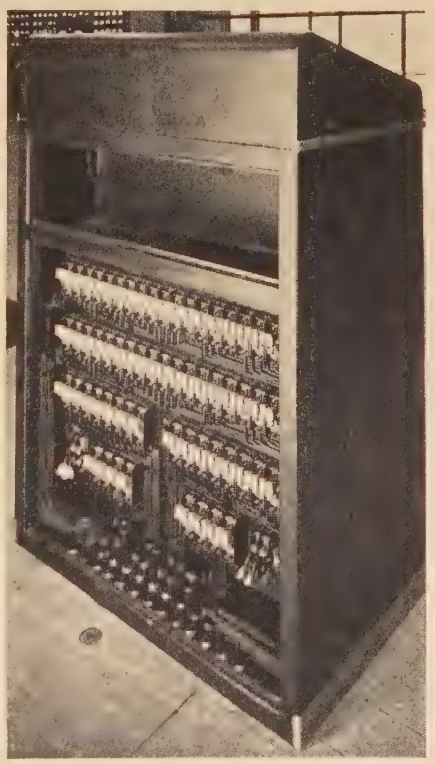


Figure 4b. Back view of standard model automatic printing ammeter

Covers have been removed to show test switches, one pair for each circuit to be measured. Completed log sheets drop into the compartment above the test switches

tacts in this rotary switch are also connected to the solenoid stops in the printing mechanism.

The totalizing sequence switch is similar to the master sequence switch except that it controls the order of procedure for the printing of totals only.

Three totalizing rotary switches are used. One switch is used for totalizing units, the second one for tens, and the third for hundreds of amperes. Their method of operation is similar to that of an ordinary odometer. Each totalizing switch has contacts connected to the points in the printing mechanism to select the correct figures to be printed.

The printer consists essentially of a small type wheel which has numerals engraved on its periphery. This type wheel is caused to rotate after the instrument has struck a balance. Solenoid stops are used to position the type wheel so that the proper number is opposite the log sheet. The type wheel is then forcibly pressed against the paper and the carriage of the type wheel is shifted to the right one space ready for the next printing operation.

A number of control buttons are mounted on a panel in front of the printer. These buttons allow the operator to type line numbers at the top of the log sheet. There are also buttons for other manual control operations.

Method of Operation

An exact description of all the connections in the instrument and the method of operation would be unnecessarily long. An abbreviated description will show the essential steps in the operation without the detailed connections. The method of operation can be traced by reference to figure 6 in connection with the description. Figure 6 is a schematic or block diagram which shows each major element in relation to its place in the sequence of operations rather than in its physical position.

The numbers in parentheses inserted in the following paragraphs refer to corresponding numbers in circles in figure 6. The numbers represent the order of the steps in which the various parts of the equipment are brought into operation.

Assume that all circuits are dead and all rotary switches are in their normal or home positions. (1). The contact-making clock closes its contacts to start the taking of a reading. Through the operation of this clock and the master sequence switch the circuit selector switch connects the first circuit to be measured with one coil of the balancing relay.

The units measuring switch is first set in a position which supplies nine amperes in one coil of the balancing relay so that, if the current in the circuit to be measured is less than nine amperes, the balancing relay will trip. However, if the current in the circuit to be measured is greater than nine amperes, nothing happens.

(2). The master sequence switch through the balancing relay next starts the tens measuring switch to rotate. Each step that this switch takes increases the current in the corresponding coil of the balancing relay by 10 amperes, so that the corresponding total pull on the relay is successively 9 amperes, 19 amperes, 29 amperes, etc., until the balancing relay trips. For example, assume the current to be measured is 36 amperes. In this case the relay trips in the third position when the pull of 39 amperes overcomes the pull of 36 amperes. The tens totalizing switch is driven synchronously with the tens measuring switch, but no connection is made from the totalizing switch to the printer at this time. (3). The tripping of the balancing relay completes a circuit through the second group of contacts on the tens measuring switch to select the correct solenoid stop on the printing mechanism to print on a log sheet the number corresponding to the tens of amperes measured (in the example, the number 3).

(4). The master sequence switch transfers the operation to the units measuring switch. The units measuring switch is first placed in the position of zero current in the units coil so that the balancing relay then has a total current less than that in the circuit to be measured. (In the example 30 amperes.) The units measuring switch then rotates, increasing the current in its corresponding coil one ampere at each step until the balancing relay again trips. The units totalizing switch also operates synchronously with the units measuring switch but does not operate the printer. (5). The tripping of the balance relay then selects through the separate contacts of the units measur-

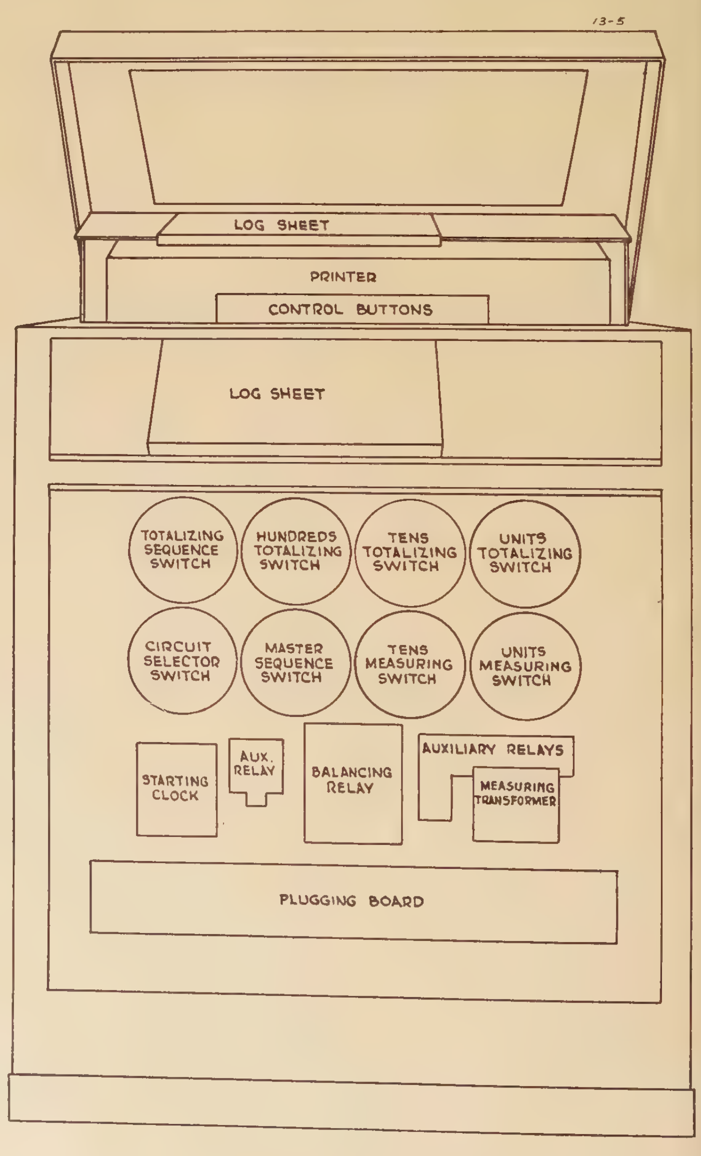


Figure 5. Outline sketch of printing ammeter

Outline sketch of front view in figure 4a on which each unit of the equipment has been labeled for identification

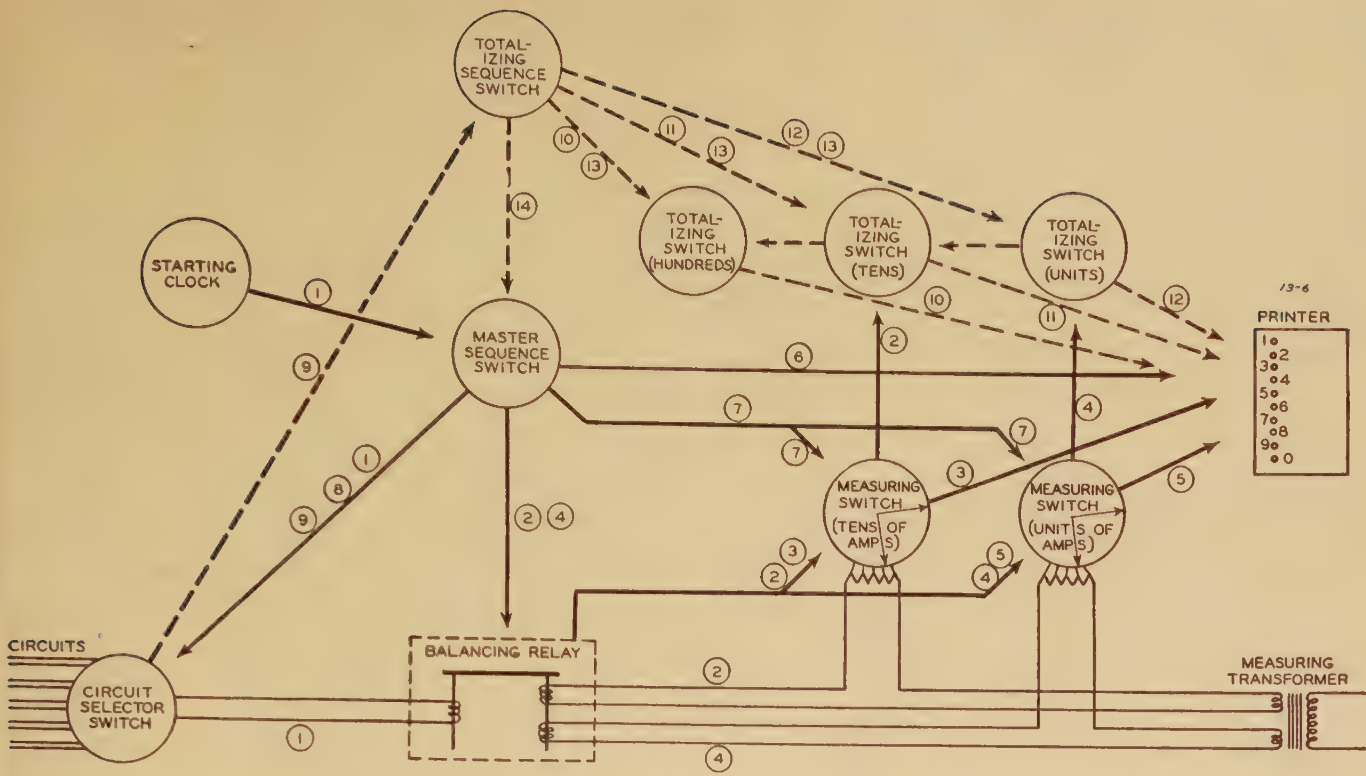


Figure 6. Block diagram for operating sequences of the instrument

Same elements are shown as in figure 5, except that elements are shown in relation to their sequence in the operation of the instrument and not in their physical position. Small numbers in circles refer to the order in which the steps are taken in the process of recording instrument readings. These numbers correspond to numbers in the description in the text

ing switch the correct solenoid stop on the printing mechanism to print the figure corresponding to the units of amperes measured (in the example, the number 6). (6). Then the master sequence switch operates the printer to space the carriage ready for the next reading.

(7). The master sequence switch next restores the tens and units measuring switches to the home position. However, the totalizing rotary switches are not restored to the home position at this time, but remain as set by the first reading.

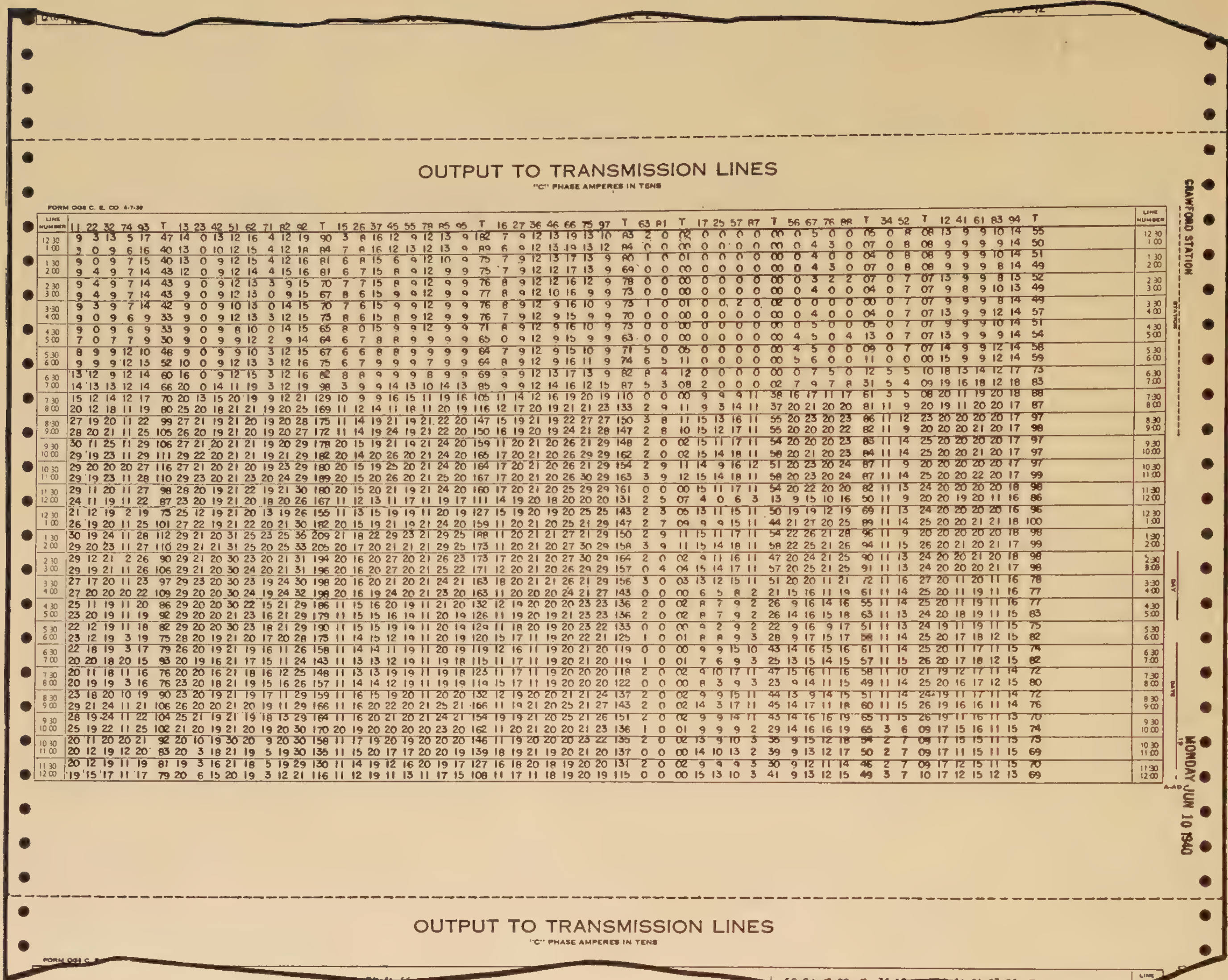
The steps just described complete the cycle of operation for taking and printing the instrument reading for one circuit. (8). The master sequence switch next advances the circuit selector switch one step in order to disconnect the first measured circuit from the balancing relay and connect the second circuit to be measured to the balancing relay. The operation of measuring and printing is repeated for the second circuit exactly as for the first.

The circuit selector switch is equipped with separate contacts by means of which a total reading can be taken after the instrument reading on any predetermined circuit. For example, it may be assumed that a total is to be taken of the first four readings. In this case the fourth instrument reading is taken according to the same procedure as before, but the master sequence switch does not complete its rotation. (9). Through the auxiliary contact in the fourth position of the circuit selector switch the master sequence switch transfers control to the totalizing sequence switch. The totalizing sequence switch then connects to the printer in turn the (10) hundreds, (11) tens, and (12) units totalizing switches to record the positions of the dials, which correspond to the total of the figures printed for the first four instrument readings. (13). The totalizing sequence switch then returns the three totalizing switches to the normal or home position and (14) transfers control back to the master sequence switch to complete its travel and go on with the next reading.

Additional equipment which is relatively simple and not shown on the block diagram is used to return the printer carriage to the home position, advance the log sheet one line for the next reading, and de-energize the instrument at the end of a complete set of readings. Other auxiliary equipment is also used to eject one log sheet from the printing ammeter and insert a new one at the end of a specified period when the log sheet is filled.

This description of the sequence of operation may create an illusion as to the length of time required for a complete set of readings. Actually the relays and switches operate much faster than the human eye can follow them. To print the readings of 45 transmission lines, grouped into ten groups, and their totals requires about two minutes total time, or two seconds per individual reading or totalizing printing.

A completed log sheet obtained from the instrument is illustrated in figure 7. The printing mechanism types across this log sheet every 30 minutes and at the end of the reading advances the sheet automatically to the next line. The right-hand and left-hand columns of figures on the printed form are the hours of the day at which each row of instrument readings was recorded. The typed numbers in the top row are the numbers of the outgoing transmission lines and the numbers below these column headings are the ampere readings in ten's on each line. The letter "T" above a column represents the column of totals for the group of line readings directly to the left of this column. For example, the first total is of the ampere readings on line numbers 11, 22, 32, 74, and 93. The picture shows also the top of the form for the following day. When the sheet is advanced automatically at the end of the day, the next form is ready for the first reading at 12:30 a.m. and the log for the day can be torn off at the perforations. In unattended substations the continuous forms can accumulate for several days in the compartment back of the printer until an operator arrives to remove them.


OUTPUT TO TRANSMISSION LINES

"C" PHASE AMPERES IN TENS

CRAWFORD STATION

MONDAY JUN 10 1940

OUTPUT TO TRANSMISSION LINES

"C" PHASE AMPERES IN TENS

Figure 7. Typical log sheet obtained from the automatic printing ammeter

Photograph shows the log sheet for one day with the bottom edge of the log sheet for the preceding day and the top of the sheet for the following day above and below the perforated lines on the continuous form. Column headings are the numbers of the outgoing transmission lines

The complete printing ammeter contains a number of relay contacts. However, not many of these contacts are involved in a particular operation. The printing ammeter shown in figure 2 has been in regular operation for about three years and has been nearly free of trouble since the initial period when it was subject to frequent tampering for the benefit of curious visitors. The instrument shown in figure 4 has been in service nearly a year. It appears that the maintenance costs on one printing ammeter for a multiplicity of lines will compare very favorably with the maintenance cost on a number of indicating ammeters, one for each line.

Fields of Usefulness

One of the major fields in which this device is very useful is in automatic or supervisory control substations. In such substations the installed cost of this multiple-circuit instrument should approximate the installed cost of individual instruments on each circuit. For such installations a traveling operator has only one instrument from which to remove records. The single record sheet is much more convenient to handle, mail, and file, than a large number of graphic instrument charts containing similar information.

In generating stations or larger substations which are attended, the elimination of the human element results in a more accurate and more legible record. All readings are taken on scheduled time as determined by the clock contacts whether or not the operator is interrupted by the telephone or other operating duties. In busier galleries there may be a saving of labor.

The instrument can be made in more portable form so that it can be used for special tests or for periodic routine load checks if desired. The plugging board, similar to a telephone switchboard, makes it relatively simple to connect circuits in any desired order for special test purposes.

For any of these applications, the instrument is appreciably more accurate than the standard switchboard type of instrument. In a device such as this where only one measuring element is used for a multiplicity of circuits, it is economical to have not only a more accurate, but a more rugged measuring element. The laboratory model of the instrument has been in service about three years, during which time the measuring element has been dismantled and put back together for check, and it has not required any recalibration to maintain an accuracy of plus or minus one per cent.

Where records are used in more than one office for various purposes, the instru-

Calculation of Initial Breakdown Voltages in Air

D. W. VER PLANCK
ASSOCIATE AIEE

ALTHOUGH spark-over and corona starting voltages can be predetermined satisfactorily in cases for which empirical formulas or curves are available, a more generally applicable method is needed. An approach to such a method is through a modification of Townsend's theory[1,1a] which, though possibly lacking in rigor, suffices in many cases for the accurate calculation of breakdown voltages. Calculations of this kind by Schumann[2] in 1923 for air in nonuniform fields were not entirely successful because of inadequate knowledge of the Townsend coefficients for air, a deficiency now remedied.[3,4,5] Loeb has discussed the modified Townsend theory at length and has applied it quantitatively to nitrogen in uniform fields.[6,7,8a]

The present paper outlines the theory and shows that the initial breakdown voltage may be calculated using two quantities characteristic of the gas for cases where the field, if nonuniform, converges toward the cathode. Formulas expressing one of the characteristic quantities for air, the Townsend coefficient α, are assembled, and a formula for the second quantity is deduced from an analysis of published spark-over gradients for plane gaps. The method is applied to two cases and the results are shown to be in agreement with experiment

Paper 41-4, recommended by the AIEE committee on basic sciences and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted October 30, 1939; made available for preprinting October 24, 1940.

This paper is part of a dissertation presented for the degree of doctor of engineering in Yale University, 1940.

D. W. Ver Planck is assistant professor of electrical engineering, Yale University, New Haven, Conn., but is on leave of absence during 1940–41 for work in the Navy Department, Washington, D. C.

1. For all numbered references, see list at end of paper.

Fundamental Considerations

Electrical breakdown of a gas depends primarily on the presence of free electrons. Their concentration, normally very small, is determined by the relative activity of the ionizing agents, radioactive emanations for instance, and the effects which cause them to disappear. Besides recombining directly with positive ions, the free electrons may be swept away by an applied field, and in air they may form negative ions by attachment to neutral oxygen molecules.

In an electric field, the electrons may gain sufficient energy to excite or ionize molecules in their paths. When the gradient exceeds 15 kilovolts per centimeter in atmospheric air, the electrons are more likely to ionize than to become attached to oxygen molecules. Then each electron as it travels toward the anode continues to make ionizing collisions, liberating more electrons which in turn multiply similarly. A single electron set free by an external agent can thus initiate an *electron avalanche* consisting of a cluster of electrons which grows rapidly as it advances and which leaves a trail of positive ions. With the field strength occurring at breakdown, an avalanche has a velocity of the order of 10^7 centimeters per second, while the positive ions left in the trail move back toward the cathode with but a hundredth of this speed. The negative ions resulting from attachment of electrons to molecules and the positive ions cannot gain sufficient energy to ionize by collision in fields attained at breakdown. The ions generated by a single avalanche disappear quickly, causing merely a small pulse of current, and the passage of a single or even many separate avalanches from cathode to anode does not necessarily result in breakdown.

There are, however, *secondary mechanisms* by which an avalanche can cause the liberation outside itself of electrons which may start new avalanches. If each avalanche initiated causes the release of at least one secondary electron in a favorable location, a self-sustaining discharge current, that is breakdown, can result from the liberation of a single electron by an external agent. The exact nature of the secondary mechanisms active in given circumstances remains a matter for speculation[8a] but a few generalizations are safe.

Two kinds of breakdown are recognized which, though they may merge, are distinct as to secondary mechanisms believed to be active. One, the *cathode initiated type*, occurs in the corona around negative electrodes and in the normal or static spark-over of short gaps. In it, positive ion bombardment or radiation from molecules excited by the avalanche causes emission of secondary electrons from the cathode surface. The other type, of which the lightning leader stroke is a manifestation, is the *positive streamer*, and occurs in the corona around positive electrodes, in the normal spark-over of long gaps, and in short gaps when more than the initial breakdown voltage is very suddenly applied. The secondary mechanism for this type is more complicated and probably involves photoelectric action in the gas and intensification of the

---

ment will produce four or five good carbon copies. In the Chicago substation three copies of the record are made, one for the operating department, one for the substation load record, and one for the distribution feeder load record. In the generating station four copies are made.

The printer need not be installed in the same cabinet with the measuring equipment. It is practicable to locate the measuring equipment near the control wiring and have the printer make the record sheet in a different room.

The present instrument is confined to ampere readings. However, it will probably be extended to other quantities such as volts or watts when the need arises.

The totalizer element of the instrument was a relatively inexpensive addition. It proved to be a valuable time saver for planning engineers because it eliminated the need of totalizing the figures in scattered columns. The hour of maximum load is obtained by scanning the total column only, and load analysis is usually made for only the maximum load.

Conclusion

This new automatic printing ammeter produces a compact record of the load on any number of circuits up to 50, with readings arranged in the form of a column for each circuit and a line for each hour of the day. The load record also includes totals for groups of lines. The following are incidental benefits derived from the use of the instrument: greater accuracy, greater legibility, duplicate records, and uniform timing of readings.

field by the space charge of successive avalanches.

This paper is concerned only with the calculation of the voltage at which cathode initiated breakdown occurs, and the question of whether the initial breakdown is a complete spark-over or a stable corona discharge is not considered.

The Townsend Coefficient α

The number of electrons n comprising an avalanche increases with distance s along the path at a rate proportional to the number already present. Thus

$$\frac{dn}{ds}=\alpha n \tag{1}$$

where α, the Townsend coefficient, is dependent on the field strength as well as the density and kind of gas. The path of the avalanche is a line of electrostatic force if the gas density is high enough so that the electron mean free path is small compared to the radius of curvature of the field line, a condition likely to be true in practice. For an avalanche initiated by a single electron from the cathode, $s=0$, integration along a line of electrostatic force gives for the number of electrons when the avalanche reaches the anode, $s=S$,

$$n=\epsilon^{\int_0^S \alpha ds} \tag{2}$$

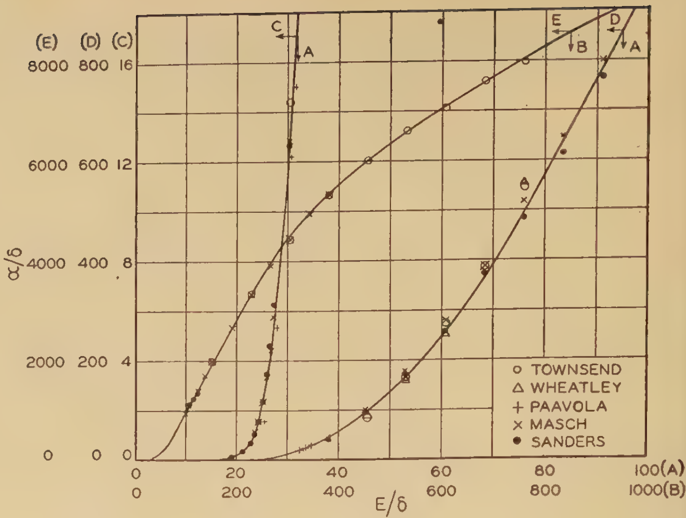
where α through its dependence on field strength is a function of s. The number of positive ions left in the trail of the avalanche is practically equal to n, although accurately it is one less since the initiating electron was emitted from the cathode.

If the avalanche grows large enough, the space charge of the ions causes the field to vary within the avalanche so that α is not the same for all of the electrons, and equation 2 is no longer true. However, certain calculations,[9] too lengthy to be included here, indicate that the field distortion caused by a single avalanche is negligibly small in a wide range of practical cases.

The method of measuring α, originated by Townsend,[1b] is based on the application of equation 2 to the continual succession of avalanches initiated by a current of photoelectrons emitted from the cathode of a parallel plane gap. Townsend found that α is related to field strength E and gas density δ by $\alpha/\delta=F(E/\delta)$ where the function F depends on the kind of gas.[1c]

Townsend,[1c,2b] Wheatley,[2b] Paavola,[4a] Masch,[5] and Sanders[3] have determined α for air with the results shown in figure 1. In this paper E is in kilovolts per centimeter and δ is the density relative to that at 760 millimeters and 25 degrees centigrade, units more convenient for calculations on atmospheric discharges than those employed by physicists, which are respectively volts per centimeter and millimeters of mercury. Density is used rather than pressure because mean free path, the significant factor, depends on density in general but on pressure only at constant temperature.

Figure 1. The Townsend coefficient α for air



The curves in figure 1 are plotted using the following empirical formulas which serve to express α for air in the ranges of E/δ indicated.

$$\left.\begin{array}{l}
\text{Range I.}\quad 15<E/\delta<25.8\\
\alpha/\delta=a_1\epsilon^{b_1E/\delta}\\
\quad a_1=1.67\times10^{-5}\\
\quad b_1=0.47\\
\text{Range II.}\quad 25.8<E/\delta<78.7\\
\alpha/\delta=a_2(E/\delta-b_2)^2\\
\quad a_2=0.166\\
\quad b_2=21.5\\
\text{Range III.}\quad 78.7<E/\delta<200\\
\alpha/\delta=a_3(E/\delta-b_3)\\
\quad a_3=19.0\\
\quad b_3=50.0\\
\text{Range IV.}\quad 200<E/\delta<467\\
\alpha/\delta=a_4\epsilon^{-b_4\delta/E}\\
\quad a_4=1.08\times10^4\\
\quad b_4=266\\
\text{Range V.}\quad E/\delta>467\\
\alpha/\delta=a_5(E/\delta)^{1/2}-b_5\\
\quad a_5=322\\
\quad b_5=850
\end{array}\right\} \tag{3}$$

Formulas for α similar in form to the first, second, fourth, and fifth of these have been given by Sanders,[3] Paavola,[4b] Townsend,[1d] and Loeb[6a] respectively, but here the constants have been adjusted for agreement with all of the data. The formulas result in curves tangent to each other at the given limits, so that for convenience in calculation the limits may be shifted slightly without serious loss of accuracy.

For $E/\delta<15$ it is assumed that $\alpha/\delta=0$; it is certainly less than 0.02, the value at $E/\delta=15$.

Cathode Initiated Breakdown

In cathode initiated breakdown a single electron released by an external ionizing agent starts an avalanche from the cathode surface. As this avalanche crosses the gap, the secondary mechanisms come into play and if they release at least one electron from the cathode, one or more new avalanches may follow. When the secondary mechanisms are sufficiently active to assure the continued repetition of this process without further action by the external agent, breakdown results.

One of the two important mechanisms by which an avalanche can cause electron emission from the cathode is through bombardment by the positive ions left in the trail. The probability that a positive ion striking the cathode will cause an electron to be released is a function of the kind of surface and the energy of the impinging positive ion. The mean free path being small, the energy for a given gas is proportional directly to the gradient E_c at the cathode surface and inversely to the density of the gas; that is, to the ratio E_c/δ. The probability that a released electron will escape diffusion back to the cathode or attachment to a neutral molecule and be able to start an avalanche also depends on E_c/δ.[6b] Thus the number N of positive ions which must strike the cathode to assure the initiation of one secondary avalanche is a function of E_c/δ and is independent of gap geometry. The condition for breakdown is that the number of positive ions left in the trail of the original avalanche must equal or exceed the number N; that is, with the aid of equation 2,

$$\epsilon^{\int_0^S \alpha ds}\geq N \tag{4}$$

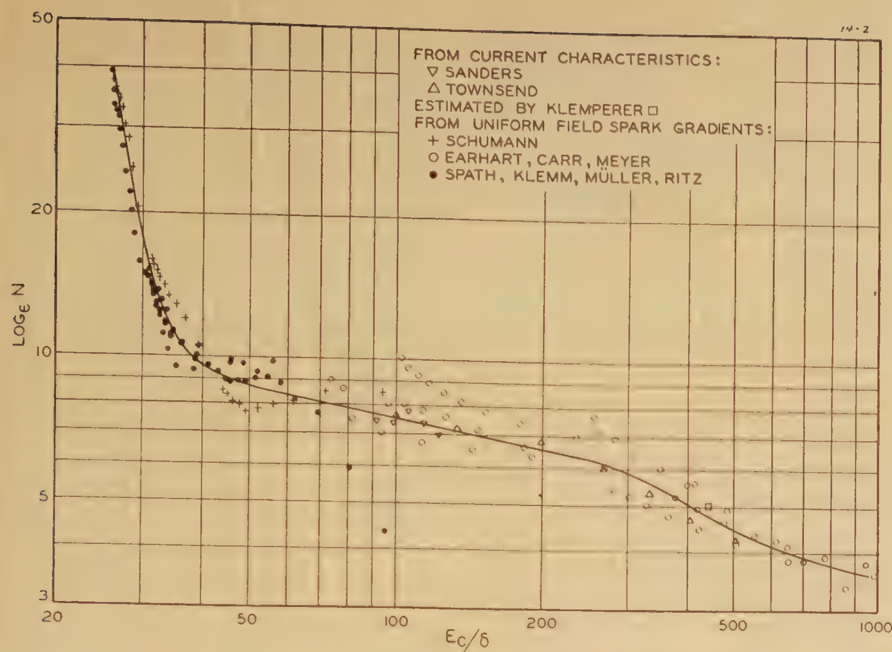


Figure 2. Log$_\epsilon$ N for air

a criterion given in the literature in various equivalent forms.[1e,6c,8a]

The other important mechanism for the release of secondary electrons at the cathode is through photoelectric action of radiation from molecules excited by the avalanche.[8a] It will now be shown that equation 4 applies approximately for this process also. The number of molecules excited by the impact of electrons is roughly proportional to the number ionized,[6d] hence the total radiation from the trail of an avalanche is proportional to the number of positive ions formed, exp $(\int_0^S \alpha ds)$. Radiation reaching the cathode surface has its greatest intensity near the starting point of the avalanche, this being nearest to all parts of the trail because the avalanche path, a line of force, necessarily starts normal to the cathode surface and in practical cases never curves sharply. For a given cathode gradient and avalanche size, the intensity of radiation at the cathode should depend on the variation of gradient with distance from the cathode because this would affect the distribution of excited molecules along the avalanche trail. However, this effect of gap geometry is probably not great and is neglected here. The number of electrons released per unit of radiation reaching the cathode depends on the properties of the surface, and as before the probability that an electron will escape attachment or diffusion back to the cathode and be able to start a new avalanche depends on E_c/δ. Thus, as with positive ion bombardment, the probability that a secondary avalanche will be initiated is a function of E_c/δ and is proportional to the number of positive ions formed by the original avalanche, and consequently equation 4 is also the criterion for breakdown by the photoelectric mechanism.

With either mechanism the secondary avalanches are most likely to be initiated near the starting point of the original avalanche, for this part of the cathode is both where the positive ions strike and where the radiation is most intense. The two mechanisms may act jointly but evidence that the time lag for spark formation in uniform fields is less than the gap transit time for a positive ion makes the photoelectric mechanism more likely,[6e] although for corona on small negative wires, positive ion bombardment probably predominates.[7]

The Number N for Air

The criterion 4 implies that breakdown occurs when exp $(\int_0^S \alpha ds)$, the number of electrons in an avalanche which has crossed the gap, equals or exceeds N, a number characteristic of the gas and dependent on the cathode gradient to density ratio E_c/δ, but independent of the type of field.

To obtain a knowledge of N for air, equation 4 was applied as the criterion for a spark in uniform field, when if the gap length is S the relation

$$\log_\epsilon N = \alpha S \tag{5}$$

follows at once. Here the right member can be determined for any value of E/δ with the aid of the empirical formulas 3 for α/δ and abundant information in the literature relating the quantities $S\delta$ and E/δ for sparks in uniform fields. In this way N can be determined for a wide range of E_c/δ, since in this case E_c and E are identical. The data used were the well known curve by Schumann[2c] based on a survey of the work done prior to 1922; results by Earhart,[2d] Meyer,[2e] and Carr[1f] which fall outside the range of Schumann's curve; and results obtained since 1922 by Spath,[10] Klemm,[11a] Müller,[12a] and Ritz.[13]

In figure 2 log$_\epsilon$ N has been plotted rather than N because it is the former that is desired for general use. While the points show considerable dispersion, a mean curve can be determined with fair certainty. This curve is expressed in the range $26<E_c/\delta<250$ by the empirical formula

$$\log_\epsilon N = 10.0(25\delta/E_c)^{0.2} + 43.0(25\delta/E_c)^{9.6} \tag{6}$$

The last term is negligible when $E_c/\delta>60$.

When positive ion bombardment is the predominant secondary mechanism, the reciprocal of N is identical with the probability γ that a positive ion impact will release an electron from the cathode. A few values of γ for air obtained from prebreakdown current characteristics are reported by Sanders,[3] and a few others may be calculated from similar data by Townsend.[1e] Points obtained from these and from an estimate of γ attributed to Klemperer[14] are included in figure 2.

Application of the Breakdown Criterion

For the calculation of initial breakdown voltages the criterion 4 is more convenient in the equivalent form

$$\int_0^S \alpha ds \geq \log_\epsilon N \tag{7}$$

The greater the inequality, the more nearly certain is breakdown, but since the left member turns out to be a function which increases very rapidly with applied voltage, the equality may be taken for practical purposes as the criterion for breakdown to be certain.

The left member of equation 7 depends on the field intensity E at every point along a line of force between the electrodes, and the right on the intensity E_c at the cathode end of this line. The field intensity, given by electrostatic theory, is proportional at every point to the voltage between electrodes if the field distortion caused by single avalanches is neglected and if no other space charges are present. Thus equation 7 gives the voltage implicitly or, if desired, the gradient at any point such as the cathode, at which breakdown will occur along the line of force considered. The breakdown voltage for

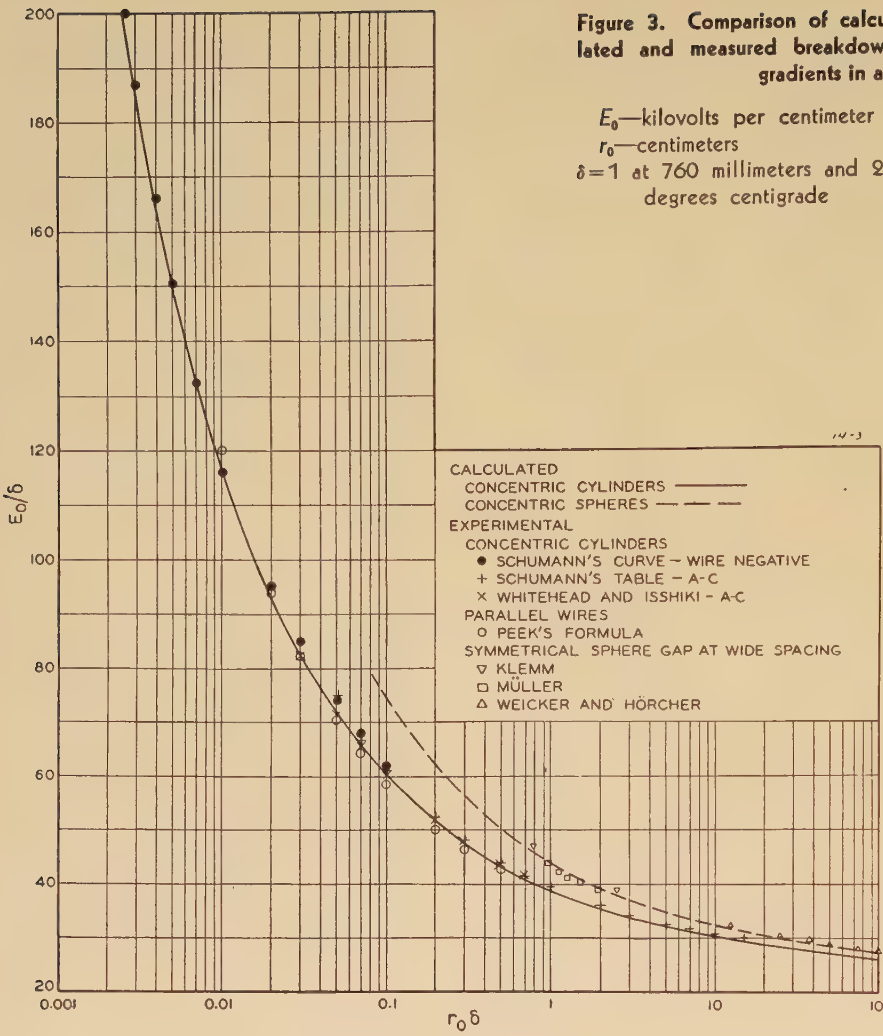


Figure 3. Comparison of calculated and measured breakdown gradients in air

E_0—kilovolts per centimeter
r_0—centimeters
$\delta=1$ at 760 millimeters and 25 degrees centigrade

a given gap is found from the line of force for which equation 7 gives the lowest voltage. In many practical cases the proper line can be selected by inspection as the shortest one.

The integration corresponds to the entire growth of an avalanche, and consequently in general is from the cathode $s=0$ along a line of force, to the anode $s=S$. However, in air if the field diverges from the cathode to such an extent that E/δ becomes less than 15 before the anode is reached, the upper limit may be taken at the point where $E/\delta=15$, because $\alpha=0$ for $E/\delta<15$.

Special consideration is necessary if the field converges again beyond a region where $E/\delta<15$. At the lower field intensities, $E/\delta<15$, the electrons are more likely to become attached to oxygen molecules than they are to ionize by collision. With no field applied, the electrons survive on the average during the motion of thermal agitation only about ten collisions with oxygen molecules before becoming attached.[15] Moreover, the electrons do not become detached from negative ions when E/δ is less than about 70.[8b] Then since negative ions do not ionize by collision in fields normally attained, an avalanche having passed through a region of appreciable extent where $E/\delta<15$ would not grow further unless it passed into a region where $E/\delta>70$. In such cases equation 7 is not directly applicable.

The breakdown criterion, equation 7, is applicable to impulse as well as to direct voltages, provided that:

1. An adequate supply of initiating electrons is maintained by the external ionizing agents.

2. The applied voltage does not change appreciably during the extremely brief time of transit of the avalanche. In the case of sphere-gaps the impulse breakdown voltage is the same as the static value if the time from the zero of voltage to the crest exceeds about two microseconds.[16]

The criterion also gives the crest value of alternating voltage at which breakdown will occur with a given electrode considered as cathode, provided in addition that:

3. Breakdown has not already occurred during the previous half cycle when the electrode in question was the anode. In the case of concentric cylinders in air there is evidence that breakdown occurs at a lower gradient when the inner cylinder, radius r_0, is negative than when it is positive for $r_0\delta<0.01$ and for $r_0\delta>0.19$ and at least up to $r_0\delta=7.0$.[2f,17,18] In the intermediate range $0.01<r_0\delta<0.19$ the breakdown gradient is not more than four per cent lower when the inner cylinder is positive.[2f]

4. The frequency is low enough for the positive ions to be swept clear of the gap during each half cycle. The critical frequency at which breakdown voltage begins to depart from its static value has been shown to vary inversely with gap length and to be of the order of 50 kilocycles for a one centimeter plane gap.[19]

Two examples of the application of the breakdown criterion will now be given.

Concentric Cylinders

For application to concentric cylinders the inner of which is negative, the breakdown criterion, equation 7, is expressed in terms of the radius r, the co-ordinate along a line of force. Thus

$$\int_{r_0}^{r_1}\alpha dr=\log_\epsilon N \tag{8}$$

where r_0 and r_1 are respectively the radii of the inner and outer cylinders. The right member is a function of the cathode gradient which in this case is the gradient E_0 at the inner cylinder.

Because α is a function of the field intensity E, it is convenient to change the variable of integration from r to E by means of the relation $E=E_0r_0/r$ for the field between concentric cylinders. Equation 8 then becomes

$$\int_{E_0}^{E_0r_0/r_1}\alpha(-E_0r_0E^{-2}dE)=\log_\epsilon N \tag{9}$$

Then

$$r_0=\frac{\log_\epsilon N}{E_0\int_{E_0r_0/r_1}^{E_0}\alpha E^{-2}dE} \tag{10}$$

which for any given ratio of radii, r_0/r_1, relates the radius r_0 of the inner cylinder to the gradient E_0 at which a negative discharge will start.

The integral can be evaluated graphically as the area under a curve derived directly from α figure 1, or analytically, using the empirical formulas 3 for α as is done in appendix A.

An important case is where the outer cylinder is quite large compared to the inner. When it is large enough so that at its surface $E/\delta<15$, that is $r_1>(E_0r_0/15\delta)$, α is zero in the space adjacent to the outer cylinder and the integration can be started at $E=15\delta$ instead of at $E=E_0r_0\div r_1$, making the result independent of r_1.

In this case when the integrals from appendix A and numerical coefficients from the formulas 3 and 6 are substituted in equation 10 and the result arranged for easy computation, there is obtained for E_0/δ between 25.8 and 78.7

$$r_0\delta = \frac{10.0\left(\frac{25\delta}{E_0}\right)^{1.2} + 43.0\left(\frac{25\delta}{E_0}\right)^{10.6}}{0.226 + 103.75\left(\frac{E_0}{25\delta} - 1\right) - 178.45 \times \log_\epsilon\left(\frac{E_0}{25\delta}\right) + 76.73\left(1 - \frac{25\delta}{E_0}\right)} \quad (11)$$

and for E_0/δ between 78.7 and 200

$$r_0\delta = \frac{7.92\left(\frac{80\delta}{E_0}\right)^{1.2}}{236.8 + 1{,}520 \log_\epsilon\left(\frac{E_0}{80\delta}\right) - 950\left(1 - \frac{80\delta}{E_0}\right)} \quad (12)$$

The results of theory and of experiment are compared in figure 3. The solid curve is a plot of equations 11 and 12. The experimental points are from a curve by Schumann,[2f] based on work of Farwell, Schaeffers, Whitehead and Brown, and Whitehead and Lee; from a table by Schumann[2g] based on researches by himself, Peterson, and Peek; from empirical formulas by Whitehead and Isshiki[17]; and from the empirical formula for parallel wires by Peek.[20] Excepting the last, all of the data are for concentric cylinders, and for either a negative inner cylinder or alternating voltage. The greatest departure of any point from the curve is about four per cent, and at that place there are other points on the opposite side. Thus the theoretical curve is in substantial agreement with experiment throughout a range of $r_0\delta$, the extremes of which are in a ratio of about 6,000 to 1.

An empirical formula often used to correlate corona starting gradients for cylinders is of the type

$$E_0/\delta = A + B(r_0\delta)^{-1/2} \quad (13)$$

where A and B are constants which have been given various values.[17,20] A plot of E_0/δ against $(r_0\delta)^{-1/2}$ as calculated from equations 11 and 12 shows some deviation from the form of equation 13, for as shown in figure 4, instead of having a constant value B, the slope first decreases considerably and then increases very slightly. Equation 13 thus does not agree with the theory although it may serve as a very convenient approximation over limited ranges.

Concentric Spheres

The breakdown criterion, equation 7, written for concentric spheres is identical with equation 8 except that r is the spherical instead of the cylindrical radius. Letting E_0 be the gradient at the surface of the inner (negative) sphere of radius r_0, the gradient at radius r is given by $E = E_0 (r_0/r)^2$ from which it follows that

$$dr = -\frac{r_0 E_0^{1/2} dE}{2E^{3/2}} \quad (14)$$

Substituting this in equation 8 and solving for r_0:

$$r_0 = \frac{2 \log_e N}{E_0^{1/2} \int_{15\delta}^{E_0} \alpha E^{-3/2} dE} \quad (15)$$

In making the lower limit of the integral 15δ, it is assumed that the region of ionization does not extend to the outer (positive) electrode.

The integral must be separated into parts corresponding to the ranges of α formulas 3, and when the integrations are carried out as shown in appendix B, there results for the case where E_0/δ is between 25.8 and 78.7

$$r_0\delta = \frac{10.0\left(\frac{25\delta}{E_0}\right)^{0.7} + 43.0\left(\frac{25\delta}{E_0}\right)^{10.1}}{0.1049 + 34.58\left[\left(\frac{E_0}{25\delta}\right)^{3/2} - 1\right] - 178.45 \times \left[\left(\frac{E_0}{25\delta}\right)^{1/2} - 1\right] + 76.73\left[1 - \left(\frac{25\delta}{E_0}\right)^{1/2}\right]} \quad (16)$$

This result is plotted as the dashed curve in figure 3. The experimental points shown, taken from curves presented by Klemm,[11b] Müller,[12b] and Weicker and Hörcher,[21] are the limiting breakdown gradients approached at wide spacings in the symmetrical gaps between equal spheres at potentials equally above and below ground.

The justification for comparing results measured for symmetrical sphere-gaps with those calculated for concentric spheres, as well as for including experimental points for parallel wires with the curve calculated for concentric cylinders, is as follows:

1. As the spacing of the symmetrical gap is increased, the field in the region surrounding the negative electrode where the ionization occurs approaches that for concentric electrodes.

2. The electrons passing into mid gap where the field is weak become attached to neutral molecules forming negative ions which cannot ionize by collision as they go on into the intense field around the positive electrode.

Conclusion

The initial breakdown voltages for two distinct types of nonuniform field have been calculated accurately by means of the breakdown criterion, equation 7, and the data contained in formulas 3 and 6, for as shown in figure 3 the results are in excellent agreement with experiment. In addition to the two examples given here, the method is being applied to breakdown between sharp edged electrodes, and it is hoped to present the results when the experimental confirmation is complete.

For the successful application of the method it is fortunate that the voltage calculated from equation 7 is relatively insensitive to changes in N because this quantity depends on mechanisms whose exact nature is somewhat obscure. Consequently the agreement of theory and experiment shown in figure 3 is not offered as proof of the correctness of the physical picture used in developing the method. There is evidence[8a] that in plane gaps where $S\delta > 0.3$, which corresponds approximately to $E_c/\delta < 35$, breakdown is not cathode initiated as assumed here but proceeds by streamer formation. However, as may be seen in the lower right hand portion of figure 3, the method yields correct results when $E_c/\delta < 35$ in spite of the possible lack of rigor in this range.

Finally it should be noted that while the data presented pertain to breakdown in air, the method is general and applicable to any gas for which the characteristic quantities α and N are known.

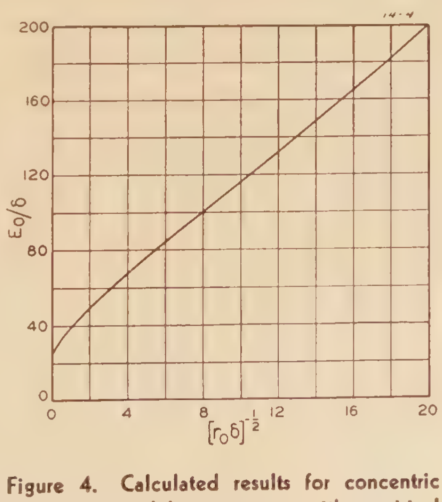


Figure 4. Calculated results for concentric cylinders tested for agreement with empirical formula of the type $E_0/\delta = A + B(r_0\delta)^{-1/2}$

Appendix A—Integration for Concentric Cylinders

The integral in equation 10 must be separated into parts corresponding to the ranges in which the formulas 3 for α apply. The extreme limits of integration are the gradients at the outer and inner cylinders, while the intermediate limits of the partial integrations are the limits of the ranges of α.

The number of ranges which must be included depends on the case considered.

When the gradient at the outer cylinder is less than 15δ and unless the inner cylinder is extremely large, the integration must go completely through range I and terminate in ranges II or III. For range I

$$a_1\delta\int_{15\delta}^{25.8\delta}\epsilon^{b_1E/\delta}E^{-2}dE = -a_1\epsilon^{b_1E/\delta}\delta/E\Big]_{15\delta}^{25.8\delta} + b_1a_1\int_{15\delta}^{25.8\delta}\epsilon^{b_1E/\delta}E^{-1}dE$$
$$= -a_1\epsilon^{b_1E/\delta}\delta/E\Big]_{15\delta}^{25.8\delta} + b_1a_1[\overline{\mathrm{Ei}}(25.8b_1) - \overline{\mathrm{Ei}}(15b_1)] \quad (17)$$

where the exponential integral function $\overline{\mathrm{Ei}}$ is defined and tabulated by Jahnke and Emde.[22a]

The integration in range II is

$$a_2\delta\int_{25.8\delta}^{E_0}(E/\delta - b_2)^2E^{-2}dE = a_2[E/\delta - 2b_2\log_\epsilon(E/\delta) - b_2^2\delta/E]_{25.8\delta}^{E_0} \quad (18)$$

For very small inner cylinders the integration must go beyond range II. Then the upper limit of 18 becomes 78.7δ instead of E_0 and integration into range III is necessary.

$$a_3\delta\int_{78.7\delta}^{E_0}(E/\delta - b_3)E^{-2}dE = a_3[\log_\epsilon(E/\delta) + b_3\delta/E]_{78.7\delta}^{E_0} \quad (19)$$

Appendix B—Integration for Concentric Spheres

The integral in equation 15 must be separated into parts corresponding to the ranges in which the formulas 3 for α apply. Treating only the case where E_0 is in range II, the entire contribution of range I is

$$a_1\delta\int_{15\delta}^{25.8\delta}\epsilon^{b_1E/\delta}E^{-3/2}dE = -2a_1\delta\epsilon^{b_1E/\delta}E^{-1/2}\Big]_{15\delta}^{25.8\delta} + 2a_1b_1\int_{15\delta}^{25.8\delta}\epsilon^{b_1E/\delta}E^{-1/2}dE$$
$$= -2a_1\delta\epsilon^{b_1E/\delta}E^{-1/2}\Big]_{15\delta}^{25.8\delta} + 4a_1(b_1\delta)^{1/2}\times\int_{\sqrt{15b_1}}^{\sqrt{25.8b_1}}\epsilon^{Z^2}dZ \quad (20)$$

where the last integral is obtained through the substitution $(b_1E/\delta) = Z^2$. Since values of this integral are available[22b] only for the range of limits 0 to 2, while the limits here are approximately 2.7 and 3.5, it is necessary to resort to a series[23] for computation.

For range II:

$$a_2\delta\int_{25.8\delta}^{E_0}(E/\delta - b_2)^2E^{-3/2}dE = a_2\delta^{1/2}\Big[(2/3)(E/\delta)^{3/2} - 4b_2(E/\delta)^{1/2} - 2b_2^2(\delta/E)^{1/2}\Big]_{25.8\delta}^{E_0} \quad (21)$$

References

1. Electricity in Gases (a book), J. S. Townsend. Clarendon Press, Oxford, 1915: (a) articles 185, 225, 293; (b) article 193; (c) article 198; (d) article 206; (e) article 225; (f) page 360.

2. Elektrische Durchbruchfeldstärke von Gasen (a book), W. O. Schumann. Springer, Berlin, 1923: (a) pages 170–232; (b) page 123; (c) page 26; (d) page 44; (e) page 56; (f) page 86; (g) page 85.

3. Measurement of the Townsend Coefficients for Ionization by Collision, F. H. Sanders. *Physical Review*, volume 44, 1933, pages 1020–4.

4. Der dunkle Entladungsvorstrom in Luft von Atmosphärendruck, M. Paavola. *Archiv für Elektrotechnik*, volume 22, 1929: (a) page 453; (b) page 456.

5. Über Elektronenionisierung von Stickstoff, Sauerstoff und Luft bei geringen und hohen Drucken, K. Masch. *Archiv für Elektrotechnik*, volume 26, 1932, page 593.

6. The Problem of the Mechanism of Static Spark Discharge, L. B. Loeb. *Reviews of Modern Physics*, volume 8, 1936: (a) pages 276–9; (b) pages 268–71; (c) pages 272–6; (d) page 268; (e) pages 284–9.

7. Fundamental Mechanisms Which Determine the Starting Potentials of the Low-Pressure Corona Discharge, L. B. Loeb. *Journal of Applied Physics*, volume 8, 1937, pages 495–6.

8. Fundamental Processes of Electrical Discharges in Gases (a book), L. B. Loeb. Wiley, New York, 1939: (a) chapter X; (b) page 291.

9. Calculation of Initial Breakdown Voltages in Air (a dissertation), D. W. Ver Planck. Unpublished, Library, Yale University, New Haven, Conn.

10. Über die Durchschlagseigenschaften von Transformatorenölen, W. Spath. *Archiv für Elektrotechnik*, volume 12, 1923, page 336.

11. Anfangsspannung und Durchbruchfeldstärke von Kugelelektroden bei Gleichspannung, A. Klemm. *Archiv für Elektrotechnik*, volume 12, 1923: (a) page 565; (b) page 571.

12. Über Durchbruchfeldstärke, Anfangsspannung und Funkenspannung bei Wechselstrom von 500 Per/sec, F. Müller. *Archiv für Elektrotechnik*, volume 13, 1924: (a) page 482; (b) page 483.

13. Durchschlagfeldstärke des homogenen Feldes in Luft, H. Ritz. *Archiv für Elektrotechnik*, volume 26, 1932, page 227.

14. Electrical Discharges in Gases, K. T. Compton and I. Langmuir. *Reviews of Modern Physics*, volume 2, 1930, page 181.

15. Atomic Structure (a book), L. B. Loeb. Wiley, New York, 1938, page 329.

16. Sphere-Gap Characteristics on Very Short Impulses, P. L. Bellaschi and W. L. Teague. *Electric Journal*, volume 32, 1935, pages 120–3.

17. The Corona Voltmeter, J. B. Whitehead and T. Isshiki. AIEE Transactions, volume 39, 1920, pages 1057–1110.

18. Der elektrische Durchschlag von Luft zwischen konzentrischen Zylindern, E. Uhlmann. *Archiv für Elektrotechnik*, volume 23, 1929, pages 326–7.

19. Die Durchschlagsenkung bei Hochfrequenz, H. Böcker. *Archiv für Elektrotechnik*, volume 31, 1937, pages 166–79.

20. Dielectric Phenomena in High Voltage Engineering (a book), F. W. Peek. McGraw-Hill Publishing Company, New York, 1920, page 46.

21. Grundlagen zu neuen Eichtafeln für Kugelfunkenstrecken, W. Weicker and W. Hörcher. *Elektrotechnische Zeitschrift*, volume 59, 1938, figure 7, page 1070.

22. Tables of Functions (a book), E. Jahnke and F. Emde. Teubner, Berlin, third edition, 1938: (a) pages 1–9; (b) page 32.

23. On the Numerical Value of $\int_0^h e^{x^2}dx$, H. G. Dawson. *Proceedings* of the London Mathematical Society, volume 29, 1898, pages 519–22.

List of Symbols

In all cases electric field strengths are in kilovolts per centimeter and lengths are in centimeters.

$a_1 \ldots a_5$,
$b_1 \ldots b_5$ = Empirical factors in formulas 3 for α

E = Field strength

E_c = Field strength at the cathode surface

E_0 = Breakdown gradient at inner cylinder or sphere

F = Function relating α/δ to E/δ; expressed for air by formulas 3

N = Number of electrons in an avalanche which has crossed the gap at the breakdown voltage, a function of E_c/δ expressed for air by the empirical formula 6

n = Number of electrons in an avalanche

r = Radial co-ordinate

r_0 = Radius of inner cylinder or sphere

r_1 = Radius of outer cylinder or sphere

S = Distance from cathode to anode along the avalanche path, a line of force

s = Co-ordinate of avalanche center measured from the cathode along a line of force

α = The Townsend coefficient for ionization by electron impact; the number of electrons added to an avalanche per centimeter of travel per electron already present (centimeters)$^{-1}$

γ = The probability that a positive ion striking the cathode will release an electron

δ = Relative air density; unity for 760 millimeters and 25 degrees centigrade

Picture Transmission by Submarine Cable

J. W. MILNOR
FELLOW AIEE

Synopsis: The direct transmission of pictorial matter over transatlantic submarine cable has become practical through the development of some special types of networks and amplifiers. These are required because of the rapid increase of the circuit attenuation with frequency, and in order to override certain characteristic electrical interference to which the cable is subject. A summary is presented of the fundamental theory which governs facsimile and telegraph transmission, and the methods are shown by which this is applied to meet the conditions of cable picture working.

An efficient system for transmission of facsimile matter from London to New York by submarine cable was made available to the public in April 1939. This provides an important advantage over radio sending of pictorial subjects, in that the cable system is not subject to unpredictable variations in the transmitting medium. But while the path from sender to receiver is inherently constant with time, the cable possesses characteristics which provide some unusual problems of transmission. The measures which were adopted to insure an undistorted likeness of the original and to transmit the intelligence at a maximum rate within the limited frequency spectrum available through the cable, appear to be sufficiently unique to justify a description at some length.

This new system should not be confused with the "Bartlane" system of picture sending which was applied to cables for several years. In the Bartlane system the picture was analyzed into small unit squares, and a code character was set up corresponding to each unit. The characters were sent by means of the equipment ordinarily serving for telegraph transmission, and were decoded, usually automatically, at the receiving end. That system was inherently slow and made inefficient use of the available cable capacity as compared with the arrangement described herein.

Description of Cable Circuit

The transatlantic cable which is utilized for picture transmission, indicated in figure 1, extends from Penzance, England to a repeater point at Bay Roberts, Newfoundland and thence to Rockaway, New York. Conductors in lead covered cable complete the circuit from London, England through Bristol to Penzance, and from Rockaway to New York City. The submarine cable contains a central copper conductor which is provided with a continuous wrapping of permalloy tape for magnetic loading, and which in turn is covered with gutta percha for insulation.

For picture transmission there are inserted repeaters of the electronic type, together with suitable signal shaping networks, at each of the above named points. The repeaters replace those in part mechanical which are in service when the cable is in telegraph operation.

In figure 2 is shown the electrical loss in each portion of the circuit, plotted against frequency.

Fundamental Transmission Requirements

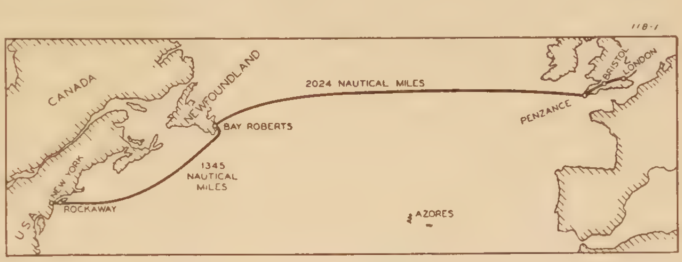
The usual practice in picture transmission is to make use of a carrier current in the path from sending to receiving terminals. However, any carrier arrangement is wasteful of the available frequency spectrum, and in the case of submarine cable working it was especially necessary to minimize any waste. Therefore a carrier is not used in the cable in the system under discussion; instead the currents correspond directly with the shades of the original picture, varying from black, which produces maximum negative current in the cable, through gray to white which corresponds to maximum positive current.

The transmission of a picture involves the sending and receiving of a large number of transient electrical currents. But every transient can be considered as the sum of a series of sinusoidal waves, and it is far more convenient to discuss the phenomena in terms of the ability of the system to transmit alternating current in a band of frequencies. In this case we are interested in the transmission from sender to receiver of all frequencies from near zero to about 110 cycles per second.

There is a definite upper limit of frequency which may be passed through a submarine cable. The cable, like radio, is subject to static interference, and because of the rapid increase in cable attenuation with frequency as shown in figure 2, the signal-to-noise ratio rapidly falls as the frequency is increased. In this cable the ratio becomes so low at about 110 cycles that currents at frequencies above this value tend to be lost in the interference. The receiving equipment is arranged to cut off shortly above this frequency in order to minimize as far as practicable the effects of outside interference.

It also is necessary to arrange the system so that the receiving equipment is insensitive to direct current or to alternating currents of very low frequency, otherwise it would be unworkable from time to time because of the earth potentials which affect ocean cables. Amounts of five volts or more occur al-

Figure 1. Route of 1926 loaded submarine cable used for picture transmission



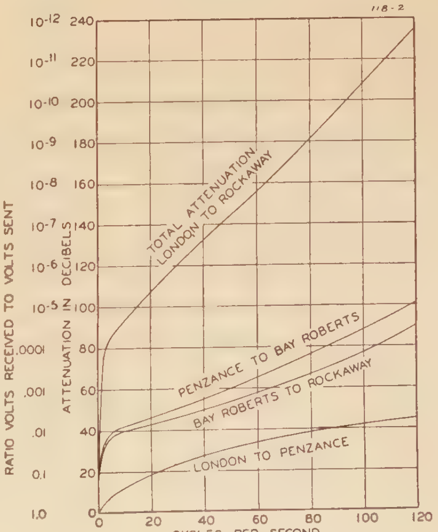


Figure 2. Attenuation of cable sections

Paper 41-18, recommended by the AIEE committee on communication and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 20, 1940; made available for preprinting December 2, 1940.

J. W. Milnor is transmission engineer for The Western Union Telegraph Company, New York, N. Y.

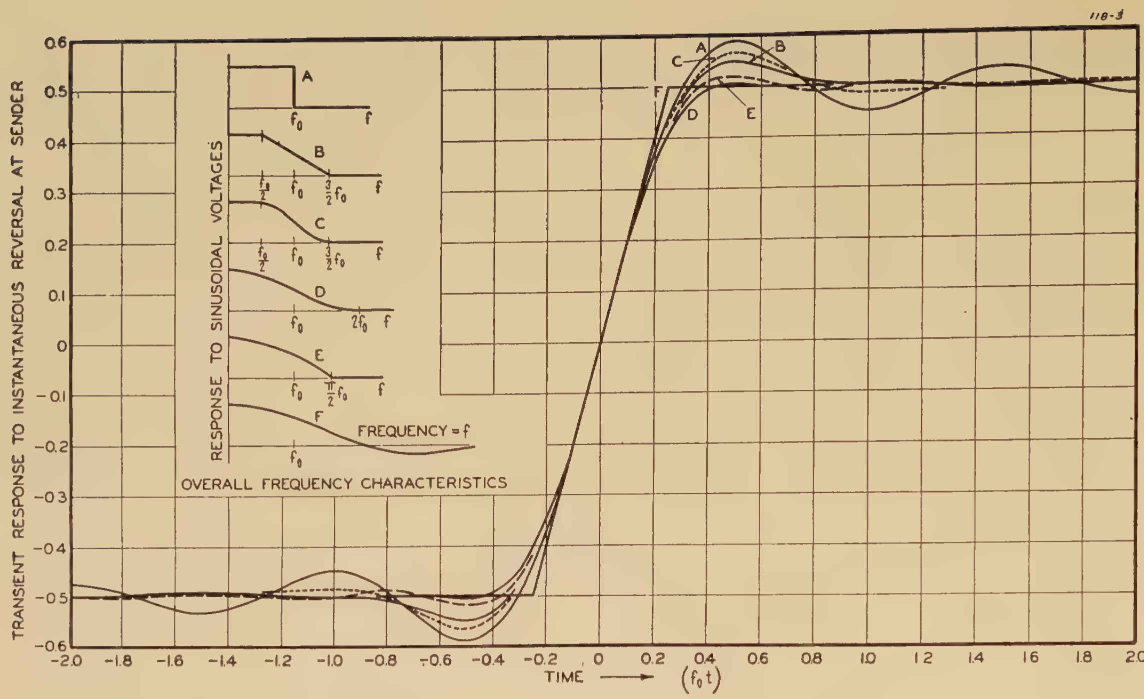


Figure 3. Arrival curves

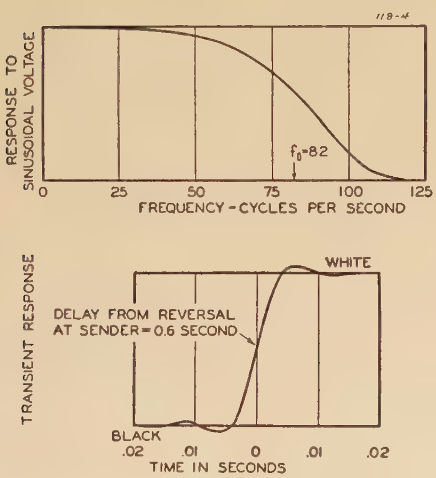


Figure 4. Frequency characteristic and arrival curve obtained over London-New York cablephoto system

most daily, and at times when abnormal conditions occur on the surface of the sun, the voltages are much higher. Values as high as 500 volts have been recorded, although such amounts occur only at long intervals. Earth potentials may be considered to be very low frequency alternating voltages, the frequency ranging from perhaps one cycle per hour to two cycles per minute. The receiving picture system is made immune to such earth potentials, except at the very occasional periods when they are unusually severe, by the shaping networks at the various points, which are arranged largely to absorb currents at frequencies of this order.

If the passage of direct currents through the cable were desirable, their transmission would in fact have been difficult because of practical considerations in the design of the amplifiers, and because of the necessity of separating from the cables the high voltage batteries used as plate supply in power amplifiers, in order to prevent the possibility of damage to cable insulation. The condensers used for the purpose have the unavoidable effect of removing most current components of the lowest frequencies.

Any arrangement of telegraph or of picture transmission in which low frequencies and direct currents are not received would be inoperable unless some arrangement were provided to compensate for the missing components of the signal. In the present case this is accomplished

Figure 5. Energy levels throughout cablephoto system

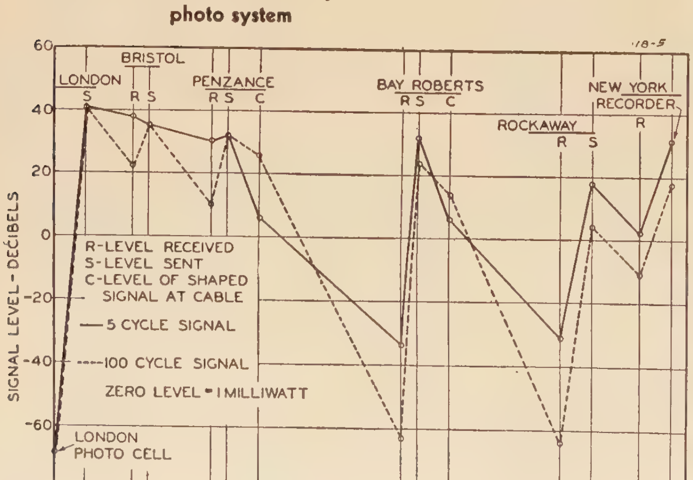
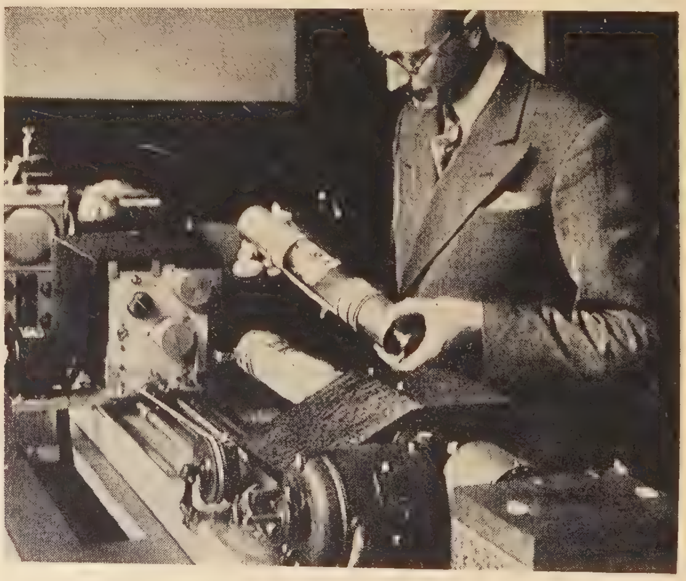


Figure 6. Cablephoto transmitter at London. Photograph sent by cable to New York



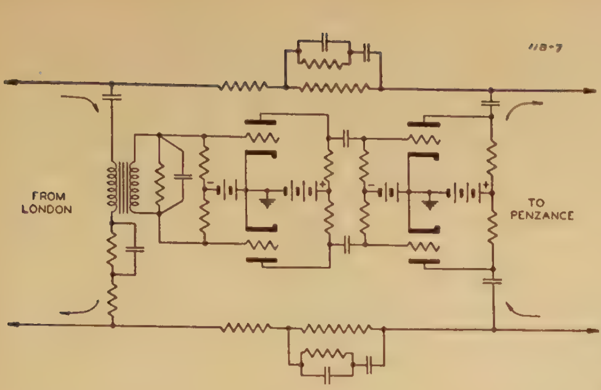


Figure 7. Repeater at Bristol

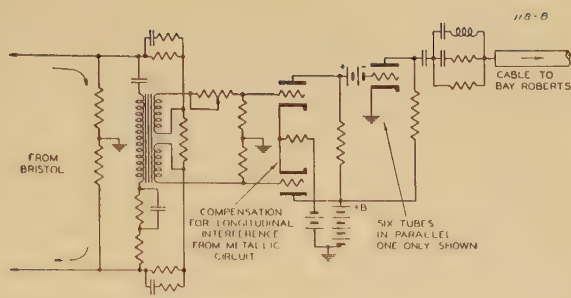


Figure 8 (right). Repeater at Penzance

by an automatic adjustment of the received signal at the end of each scanning line in the picture. At that moment it is arranged to reduce to zero (corresponding to neutral gray in the picture) the current at the sending station. At the corresponding time there is cut into the circuit at the receiving station a set of equipment which measures the amount of current being received and automatically compensates for the current level if it departs from normal. Thus the next scanning line is started with the received level at its correct value.

In its passage through the system, the facsimile signal must be amplified sufficiently to overcome the cable attenuation at the highest frequency that is utilized, in addition to the unavoidable loss of energy in various elements of the equipment. The total available amplification from the sending photocell to the receiving lamp is approximately 420 decibels.

The shaping networks at various points perform the functions discussed in the past few paragraphs, and in addition they discriminate between different frequencies in a manner to compensate with some precision for their large difference in attenuation and phase shift in the cable. For example, a current at five cycles is reduced as much as 109 decibels, as compared with that at 100 cycles, by the shaping networks.

Theory of Signal Shaping

The combined effect of the shaping networks at all points determines the faithfulness of the final product and the efficiency of utilization of the available frequency spectrum. The problem is parallel to that encountered in telegraphy in endeavoring to transmit a maximum quantity of material within a given range of the frequency spectrum.

When a reversal from black to white occurs at the sending transmitter, the effect reaches the distant recorder in the form of an "arrival" voltage, rounded somewhat and possibly otherwise distorted from the shape of the current as sent. Each possible arrival curve corresponds to a definite "frequency characteristic" of the entire transmission system, which is the ratio of received to sent voltage plotted as a function of frequency, assuming that the transmitter has been replaced by a generator of sinusoidal currents. The choice of the frequency characteristic markedly influences the efficiency of the system.

The frequency characteristic comprises in general both an amplitude function and a phase function. An arrival curve is not received at the same instant that the reversal occurs at the transmitter; instead there is a slight delay, and that lag corresponds to a change in phase angle which is proportional to the frequency. Such a phase change is not of importance as affecting the efficiency. If such phase changes only are present the arrival curve is symmetrical. Basic theory* shows that any phase change other than in proportion to the frequency, which introduces components in the frequency characteristic in quadrature to the main component, causes the arrival curve to be nonsymmetrical. Such a phase response makes less effective use of the cable capacity.

Since the attenuation of a cable increases rapidly with frequency, and the higher frequencies are increasingly difficult to utilize, it might be expected that the preferred over-all frequency characteristic would be one which cuts off sharply at the upper end of the useful range. Investigation, however, shows that such a characteristic is associated with an arrival curve which oscillates to an objectionable extent both before and after the main reversal.

Plots of a number of symmetrical arrival curves, with their corresponding frequency characteristics, are illustrated in figure 3**. The characteristics have been so chosen (with equal area under each) that the maximum slope of each arrival curve is the same. The amount of resolution in the direction of scanning is approximately proportional to the mean frequency f_0. The effect of an abrupt cut-off of the characteristic is shown in curve A.

Entire freedom from oscillations in the arrival curve requires the use of a characteristic which with increasing frequency decreases quite gradually to zero, and which therefore is quite wasteful of cable capacity. Curve D is an example of such a characteristic. However, a desirable compromise between the efficiency of cable utilization and the appearance of the resulting picture is obtained by permitting a moderate overthrow and oscillation in the arrival curve, which is not objectionable and may be of advantage in accenting the lines of the image.

Frequency characteristics precisely like those just shown, and with the correct phase angles, could hardly be obtained through the use of equipment which it is practical to assemble, but fairly close approaches should be feasible providing that networks of sufficient complexity are used. The arrival curve and the amplitude of the frequency characteristic actually obtained over the cablephoto system are shown in figure 4. Phase angle changes, other than those proportional to frequency, are small, and the arrival curve therefore is nearly symmetrical.

Amplifying Equipment

A number of unique problems were encountered in providing the necessary amplification and signal shaping at various points along the route. The manner in which the signal level varies from point to point is indicated in figure 5.

The transmitter in London, figure 6, contains a light shutter ahead of the photocell which breaks the beam at the rate of 1,350 times per second. The output of the photocell in the form of a carrier is amplified, demodulated, again amplified and impressed upon the line in the form of a signal in which the various voltages from maximum negative to

*Submarine Cable Telegraphy, J. W. Milnor. AIEE Transactions, February, 1922. Note equation 10 in the appendix, which served for computations of the arrival curves included herein.

**In this figure the frequency characteristics C, D, and E are portions of sine or cosine curves as shown. The characteristic F is of the form $2f_0/\pi f \sin \pi f/2f_0$.

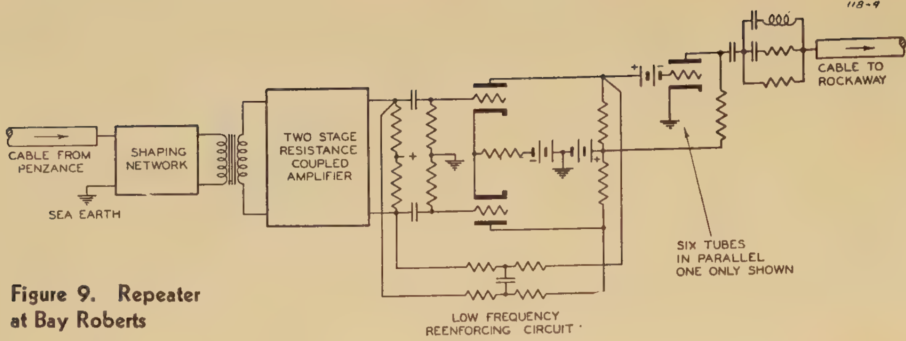


Figure 9. Repeater at Bay Roberts

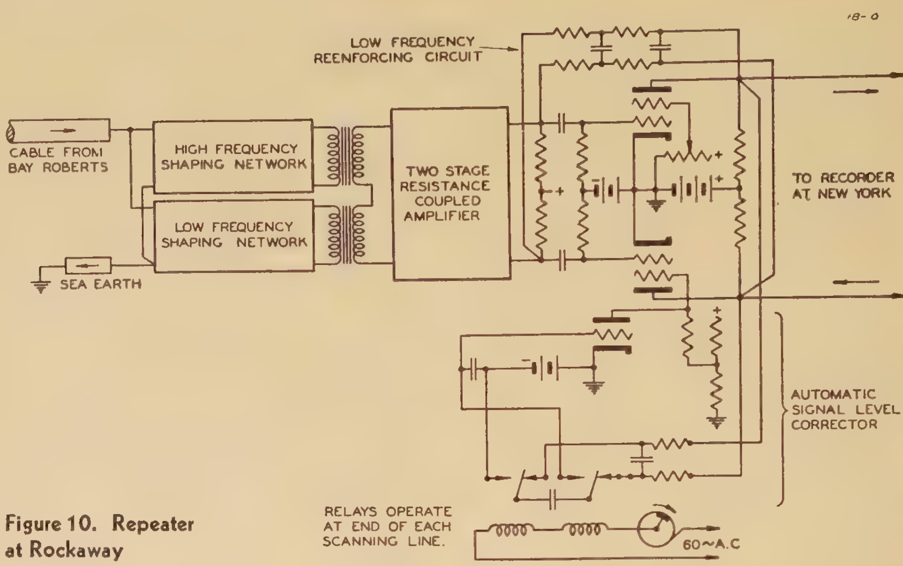


Figure 10. Repeater at Rockaway

maximum positive correspond to the shades from black to white. The wires which are available from London to Bristol and from Bristol to Penzance, set up as a metallic pair, are capable of handling frequencies somewhat above 120 cycles per second, but are not suitable for carrier working.

At Bristol the currents are passed through a type of repeater, figure 7, which in the interest of simplicity is arranged to amplify the higher frequency components only. The lower frequency components are by-passed around the amplifier.

At Penzance, figure 8, the currents are received from a metallic pair and after amplification are sent into a submarine cable which makes use of ground return. The metallic pair, while relatively free from interference between the wires, is subject to serious longitudinal interference. The problem of passing into a ground-return circuit the wide frequency range of the needed currents, while avoiding the longitudinal interference, is met by the use of a push-pull amplifier including a degenerating arrangement which renders it insensitive to longitudinal voltages, while amplifying the transverse signal voltages from the incoming pair.

The transformers and the condensers which were placed in circuit at certain points because of practical considerations, have the unavoidable effect of largely reducing some of the desirable frequency components in the signal, particularly those components below about 0.4 cycle per second. To correct for this loss there is inserted in the repeater at Bay Roberts, figure 9, and again in that at Rockaway, a network which through feed-back action serves to re-enforce the lowest frequencies, while having no influence upon the higher ones.

Shaping networks in addition to those just described are included at all points except at the terminals for the purpose of attenuating currents at the intermediate frequencies and controlling the phase angle to compensate for the varying attenuation of the cable at different frequencies. The complete transmission system is effective throughout the range from about 0.04 cycle per second to about 110 cycles, which is a ratio of highest to lowest frequency of about 2,750 times.

At Rockaway, figure 10, the currents after amplification are adjusted in level automatically in the manner previously described, at the end of each scanning line, in order to compensate for the absence of signal components below about 0.04 cycle per second. At that instant, because of the momentary reduction to zero of the output from London, the output of the Rockaway amplifier should also be zero. The relays in the automatic corrector are caused to vibrate rapidly at that time. If any difference in potential then exists across the amplifier, the grid of one of its tubes is adjusted quickly until the difference in potential is removed.

The output of the repeater at Rockaway is passed on to New York, and is there again amplified and impressed upon a gas-filled lamp which serves to expose the receiving photographic film.

Results

Typical photographs transmitted by cable are shown in figures 6 and 11. These were transmitted at the rate of 2.2 square inches per minute, with scanning at 60 lines per inch. The resolution in the direction of scanning is especially fine, and is sufficient to warrant an increase either in the number of scanning lines per inch or a decrease in the time of transmission of a given area of picture.

Times Wide World

Figure 11. Trafalgar Square. Photograph transmitted by cable from London to New York

The Audio Noise of Transformers

W. C. SEALEY
MEMBER AIEE

Synopsis: When transformers are installed near inhabited districts, their noise must be limited to unobjectionable values. Consequently, means of predetermining noise levels from the design constants of the transformer and means of noise reduction become necessary. It has been determined that the audio noise of transformers originates in the change in dimensions (magnetostriction) produced in the core steel by the alternating magnetic flux. The vibration caused by the change in dimensions is transmitted to the air through the tank walls. The basic noise may be increased due to the resonant vibration of mechanical parts. Theoretical relations for the sound produced have been derived. These relations are checked by tests on commercial transformers.

Introduction

WHEN power transformers are installed in locations remote from residences or other buildings used constantly by human beings, audio noise created by them is not a problem. However, as loads increase it becomes desirable to place larger transformers closer to inhabited districts. Large transformers can create sufficient noise as to make their presence in inhabited districts objectionable. In addition, the public is becoming more noise conscious and insistent on the elimination of objectionable noise of any kind.

Consequently, the calculation of the noise of a transformer from its design constants in order to predict the amount of the noise and a study of means of noise reduction becomes a practical necessity.

Origin of Noise of Transformers

Audio noise of transformers originates in the change in dimensions produced in the core steel when it is magnetized.

When iron is magnetized, its dimensions change due to the magnetization. Usually, the iron lengthens parallel to the flux lines and decreases in dimensions at right angles to the flux lines. The change in dimensions is extremely small. For example, a typical transformer punching 100 inches long will increase in length 0.0002 inches when the transformer is excited at full voltage.

Figure 1 shows percentage changes in length for typical transformer steel. Although small, the change in dimensions sets up sound waves in the manner common whenever rapid movement of a solid (in this case the steel) in contact with an elastic medium (air or oil) occurs. The intensity of the sound (in watts per square centimeter or similar units) is proportional to the square of the amplitude of vibration. When the magnetizing force is alternating as in a transformer, the sound waves issue continuously. Such is the source of noise in a transformer. Its origin is the vibration of the iron core caused by the change in dimensions commonly called magnetostriction.

Measurement of Noise*

A method of predetermining the noise of a transformer from its design is the first step in designing a quiet transformer. This requires, in turn, a satisfactory means of measuring noise and convenient units for expressing the amount of noise.

Noise can be expressed in a wide variety of ways. A fairly complete description would be a curve of watts per square centimeter versus time. It is obvious that such a curve does not lend itself to ready comparison and analysis. Recurrent sound may be expressed as the sum of its various harmonics each expressed in terms of its maximum amplitude. Such an expression is useful for sound analysis and is frequently used for this purpose in noise reduction. It may be obtained by recording the curve of intensity versus time and analyzing it into its harmonics, or by the more usual process of obtaining each harmonic separately by a harmonic analyzer.

However, such measurements do not result in the simplicity necessary for convenient general use. It is highly desirable to have a method of measurement of noise or sound intensity which can be expressed in terms of a single unit.

Such measurement is complicated by the fact that the human ear which is the final arbiter of noise has a different response for each different frequency of sound and in addition, the comparative response varies with the amplitude of the sound.

To take account of the variation in response of the ear to the various frequencies, the measurement must give weighted values to the intensities of the various frequencies. Standard curves for such weighting have been established. Using these curves as a base, the common method in use today for giving an over-all expression of the amount of noise is to express it in decibels. For example, a particular sound is said to have an intensity of 60 decibels.

The decibel is really the measure of the ratio of two amounts of power. Since the human ear responds to an extremely wide range of sound intensities, the decibel offers a convenient means of expression of sound intensity. The decibel is so expressed mathematically that the sound intensity increases ten times for each ten decibels increase in sound level. Mathematically the sound level in decibels=

$$10 \log_{10} \frac{I}{I_0}$$

where I_0 is the reference intensity for the scale in watts per square centimeter or similar units and I is the measured intensity in the same units. The reference level I_0 in common use at present is 10^{-16} watts per square centimeter which at a temperature of 20 degrees centigrade and a pressure of 760 millimeters of mercury corresponds to a pressure of 0.000204 dynes per square centimeter for plane or spherical free waves. Expressed in terms of the pressure, the sound level in decibels, db $= 20 \log \frac{P}{P_0}$ where P_0 is the reference sound pressure in dynes per square

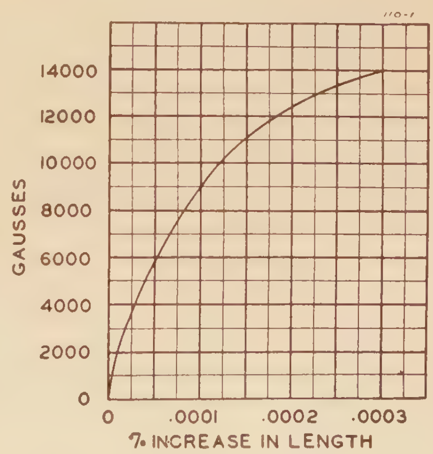


Figure 1. Typical magnetostriction curve of high-silicon transformer steel

Paper 41-10, recommended by the AIEE committee on electrical machinery and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted September 19, 1940; made available for preprinting December 19, 1940.

W. C. SEALEY is electrical engineer in the transformer division of the Allis-Chalmers Manufacturing Company, Milwaukee, Wis.

* Further information can be found in the American Tentative Standards Z24.1, Z24.2, and Z24.3, and AIEE test code No. 520.

centimeter or similar units and P is the measured sound pressure in the same units. Suitable instruments have been developed for measuring the over-all sound level in decibels. Other instruments have been developed for analyzing a sound into its harmonics. At the present time these are not precision instruments in the same sense that the more common electrical measuring instruments are. However, they are sufficiently accurate to be extremely useful in sound level determination. One of the obstacles has been the difficulty of calibration so that readings with the same meter or other meters calibrated at different times will be the same.

Theoretical Variations of Sound With Weight

Based on these methods of expressing and measuring sound, theoretical relations for the noise of transformers are derived. It is general experience that the noise of a transformer varies with its size and that large transformers are usually more noisy than small transformers.

It is also well known that the noise of a given transformer increases as the applied voltage is increased. That is, the sound level of a transformer increases as the induction in the iron is increased.

According to the standards which have been established for measuring transformer noise, the sound intensity is measured one foot away from the major sound producing surface. Consequently the sound intensity measured is practically the sound intensity at the surface of the sound transmitting member.

The first relation derived is that between sound intensity and the weight of the transformer core. For transformers of similar proportions the core weight, W, is proportional to the length of the core L, raised to the third power.

Thus $W=K_1L^3$ where K_1 is a constant

When the transformers considered have the same induction in the iron core, the noise intensity, I, at the outside of the transformer is proportional to the square of the core length because of the general law that the noise intensity is proportional to the square of the amplitude of vibration and because the change in dimensions due to magnetostriction is proportional to the core length.

Thus $I=K_2L^2$ where K_2 is a constant

$$L=\frac{(W)^{1/3}}{(K_1)^{1/3}}$$

Substituting for L in: $I=K_2L^2$

$$I=K_3W^{2/3} \text{ where } K_3=\frac{(K_2)}{(K_1)^{2/3}}$$

or the noise intensity is proportional to the weight of the core raised to the two-thirds power when the induction in the iron is constant.

Since the sound level in decibels, db by definition, equals

$$10\log_{10}\frac{I}{I_0};\ \text{db}=10\log_{10}\frac{(K_3W^{2/3})}{(I_0)}$$

$$\text{db}=10\log_{10}\frac{(K_3)}{(I_0)}+\frac{20}{3}\log_{10}W$$

Where $K_4=10\log_{10}\frac{(K_3)}{(I_0)}=$ a constant when the reference intensity I_0 is constant

$$\text{db}=K_4+\frac{20}{3}\log_{10}W$$

or the noise level in decibels is equal to a constant plus 6.67 times $\log_{10}$ (weight).

From this relation, it is evident that changing the reference level does not change the slope of the curve, but merely the value of K_4.

Theoretical Variation of Sound With Induction

The second relation derived is that between sound intensity due to magnetostriction and the maximum induction in the iron. The curve of change in length due to magnetostriction (figure 1) is obtained from tests on small samples of iron tested one sheet at a time in a device for determining the change in length due to magnetization of the sheet.

If S is the per cent increase in length due to magnetostriction, and K is a suitable factor, the sound intensity, I, for a given transformer is equal to KS^2. If the relative proportions of the different harmonics of the sound to each other remain the same with variation in S, K will be a constant. This derivation applies to all cases where K may be assumed to be constant with permissible error.

If S_0 is the per cent increase in length for reference level of induction B_0, the sound intensity, I_0, at the reference level is equal to KS_0^2.

Since the sound level in decibels, db by definition equals $10\log_{10}\frac{I}{I_0}$;

$$\text{db}=10\times\log_{10}\frac{S^2}{S_0^2}=20\log_{10}\frac{S}{S_0}.$$

If in figure 1, the reference level is chosen as 12,000 gausses $S_0=0.000177$ per cent, and $\text{db}=20\log_{10}\frac{S}{0.000177}$.

By substituting values of S from figure 1, values for plotting curve A of figure 2 are obtained. Curve A of figure 2 shows the change in sound level in decibels, due to magnetostriction when the maximum induction in the iron changes.

Tested Variation of Sound With Induction

Curve B of figure 2 was obtained by testing with a sound level meter the sound intensity of complete commercial transformers. The values of decibels read on the meter were corrected to a reference level of 12,000 gausses by subtracting the db at 12,000 gausses from the values at other inductions. It will be noted that the agreement between curves A and B of figure 2 is very close. This is an indication of the correctness of the theoretical analysis and in addition an indication that the origin of the noise was the magnetostriction of the iron with at most a negligible quantity of noise from other sources.

If steel having different magnetostriction characteristics were used, curves similar to figure 2 for the different steel would be used for sound intensity determinations. For certain cases, accurate determination of curve A is involved but curve B can always be obtained directly from sound intensity measurements.

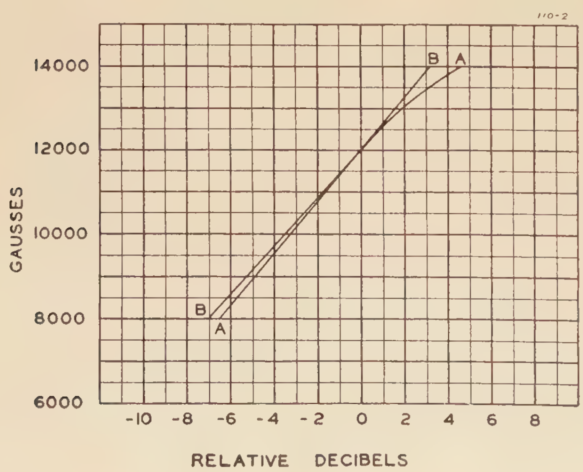


Figure 2. Variation of sound intensity with induction

Curve A—From magnetostriction tests on steel

Curve B—From sound level tests on complete transformers

Tested Variation of Sound Level With Core Weight

In order to check the correctness of the derived relation between noise in db and the core weight, a large number of sound level tests made on commercial transformer both in the shop and in the field were compared with calculated values.

Most of the tests were made at normal flux density for the transformers and in order to compare the values, they were reduced to a common flux density of 12,000 gausses. The values plotted in figure 3 are the sound intensity corrected to an induction of 12,000 gausses and the actual weight of the iron core in per cent of a common base.

The figure of 12,000 gausses to which the sound levels were corrected was chosen as being near the average induction of typical transformers. The correction was made by the use of figure 2. If W is the total weight of the core, W_1 is the weight of the part of the core considered, and its induction during the noise test was B_1, the value from figure 2 corresponding to B_1 was F_1, and the correction in db due to the part of the core considered was C_1, then $C_1=\left(\frac{(F_1W_1)}{W}\right)$. These corrections are obtained for the various parts of the core and added algebraically. In order to correct the sound reading obtained by test to the sound level corresponding to 12,000 gausses for plotting, the correction is subtracted algebraically from the test value. This method of making the corrections, is of course, an approximation but for the small variation in flux density which existed, the error introduced is negligible.

For example, a transformer has a tested noise level of 62 decibels. The weight of the core steel, W_1, is 2,000 pounds; B_1 its induction is 12,500 gausses; the weight, W_2, of the yoke steel is 3,000 pounds, its induction B_2 is 11,000 gausses. From figure 2, F_1 on curve A corresponding to 12,000 gausses is 1.0, F_2 corresponding to 11,000 gausses is -1.7.

$$C_1=\frac{F_1W_1}{W}=1.0\times\frac{2{,}000}{5{,}000}=0.4$$

$$C_2=\frac{F_2W_2}{W}=1.7\times\frac{3{,}000}{5{,}000}=-1.0$$

$$C_1+C_2=0.4-1.0=-0.6$$

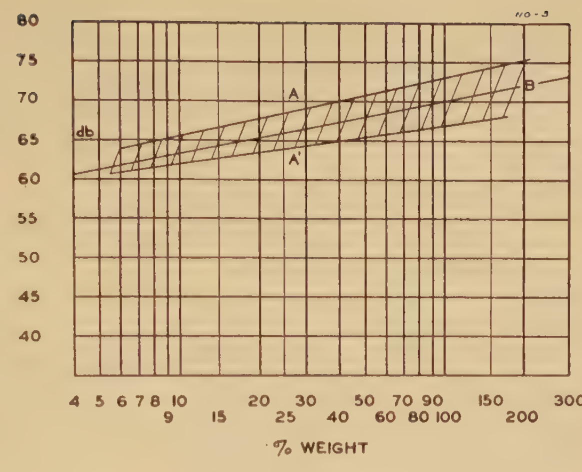
The sound level of the transformer corrected to 12,000 gausses is $62-(-0.6)=$ 62.6 decibels.

This is the value which would be plotted in figure 3. Values obtained in this manner were plotted and the curves of figure 3 were obtained.

Figure 3. Variation of sound intensity with weight of core

Band A—A' indicates test values

Curve B—Theoretical curve



To obtain quantitative results from the data given for a particular transformer, the procedure is to obtain the decibel value for the transformer from figure 3 corresponding to the total weight. This is the decibels of the transformer at one foot provided all the iron were at an induction of 12,000 gausses. If the induction is at some other value, a correction for induction is made using figure 3.

Example

A transformer with the following characteristics is assumed:

Core weight	30 per cent of the base weight
Yoke weight	50 per cent of the base weight
Total core weight	80 per cent of the base weight
Core induction	12,800 gausses
Yoke induction	11,500 gausses

The decibels corresponding to 80 per cent of the base weight on figure 3 is 69.3. From figure 2, curve A, the corrective decibels for the core =

$$\frac{30}{80}\times 1.6=0.6$$

The corrective decibels for the yoke = $50/80\times -0.9=-0.56$

The corrected decibels $=69.3+0.6-0.56=$ 69.34 decibels

The tested values as corrected for induction are shown by the shaded area between the lines A and A'. The straight line B is drawn through the approximate center of the band with a slope so that the sound intensity varies as the two-thirds power of the core weight. The slope of this line is the same as the slope of the shaded area within the limits of experimental error.

The weights in figure 3 are given as a percentage of an arbitrarily chosen base weight. The same curve can be used for other proportions or forms of construction after the correct base weight has been determined experimentally. The band width of the curves of figure 3 is due partly to variation in the magnetostriction of the steel itself. Some of the high points outside the band were probably due to resonance phenomena involving mechanical vibration of some part of the transformer.

Measurements on identical transformers extended over a large part of the band width. Physical proportions of the transformer also affect this sound level.

It was found that radiators had little effect on the sound level when the sound level was measured at one foot from the major sound producing surface in accordance with the latest standards. This is not wholly unexpected because the sound travels through oil and metal with little attenuation, and the sound wave transmitted is extremely complex.

In general, transformers with higher exciting currents, compared with identical transformers produced higher sound levels, but additional investigation is required before general conclusions on this subject can be offered with confidence.

Reduction of Noise

The reduction of the sound level of transformers is most effectively secured by reducing the induction in the iron. To produce quiet transformers, it is necessary that parts be so constructed that reasonant vibration is negligible. No successful method of reducing the transmission of sound to the air has been developed so far.

Generally most of the objectionable sound is borne by the air. In cases where sound is conducted through the supports, sound isolating devices may be used but the solution is difficult owing to the large low frequency components of the sound.

In the future, noise reduction through steel of lower magnetostriction may be expected.

The most variable quantity at present is the magnetostriction inherent in the

The Electric Strength of Air at High Pressure—II

H. H. SKILLING
MEMBER AIEE

W. C. BRENNER
ENROLLED STUDENT

Synopsis: Results are given of an investigation of the electric strength of air at pressures up to 21 atmospheres. Sparking voltages are presented for air under pressure as measured with 60-cycle alternating voltage applied to sphere gaps. Deviation from the linear pressure-voltage relation that exists at low pressures is discussed, and certain characteristics of sparking in compressed air are noted.

A STUDY of the electric strength of air under pressure was reported three years ago.[1] Because of increased interest in the subject this study has been extended, and parts of the work have been repeated with a higher degree of accuracy. Data thus obtained are of interest in the design of air-blast circuit-breakers and other types of compressed-air switches, gas-insulated transformers, power cables operating under pressure, gas-filled radio transmitting condensers, etc.

The present paper presents data relating to sparking between spherical electrodes in air, the air pressure ranging from 1 to 21 atmospheres (0 to 300 pounds per square inch gauge pressure). Results obtained with spherical electrodes may be applied with reasonable accuracy to any spark gap in which the electric field is substantially uniform. The results of this investigation are therefore applicable to sparking between the parallel plates of condensers, electrostatic shields of high-voltage apparatus, and other smooth surfaces. Breakdown between points, and at sharp edges, and between small wires, is discussed in the earlier paper.[1]

Apparatus

The spherical electrodes of the test gap, mounted in their supporting framework, are shown in figure 1. The spheres shown are approximately 20 millimeters or slightly less than one inch in diameter. The upper sphere is supported by means of a glass plate which insulates it from the metal framework. The stem of the upper sphere is electrically connected, through a spring, to the metal rod at the axis of the two glass cones near the top of the picture. These cones, clamped back-to-back, constitute the high-voltage bushing for the pressure tank in which testing is done. The axial rod through the cones serves as the high-voltage lead into the tank, and a connecting wire from the top of the rod to the high-voltage transformer may be seen in the picture. The heavy metal disk between the glass cones becomes the head of the pressure cylinder when the apparatus is assembled.

The lower sphere is adjustable vertically by means of a micrometer mechanism. The sphere may be raised or lowered without rotation. Springs are provided to prevent error due to backlash in the screw or bearings. To adjust the gap between spheres to its desired value the lower sphere is raised until it touches the upper sphere. Contact is indicated by a neon glow lamp that is connected in series with the gap while making this adjustment. The lower sphere is then lowered to its proper position as indicated by the micrometer calibration. Micrometer settings are read to 0.0001 inch.

The supporting framework for the gap is quite rigid. It is subjected to no stress other than its own weight, and the gap length is adjusted in the same position in which electrical testing is done. In particular, the supporting framework is so designed that changes of pressure of the gas do not change the length of the spark gap, as would occur if the spheres were supported from opposite ends of the tank. Temperature changes are not large, and since all major parts of the supporting framework are of the same material (steel) the gap length is not appreciably affected by expansion or contraction.

Dimensions and clearances are such that the gap is essentially a standard sphere spark gap as defined by AIEE standards.

For testing in gases other than air at atmospheric pressure the assembly shown in figure 1 is inserted in a pressure chamber as shown in figure 2. The cylinder, a 29-inch length of 10-inch steel oil well casing, is closed at top and bottom by heads of cast steel that are clamped together by 12 bolts as shown. Provision is made to admit gas to the test chamber through a pipe at the top, and two electric circuits other than the high-voltage circuit are led into the chamber by means of spark plugs. One of these circuits is used for a lamp to illuminate the interior of the chamber, and the second serves to operate a fan, to supply a source of ultraviolet radiation, and for other purposes as required. A shaft carried through a stuffing-box in the upper head allows adjustments of the spark-gap length to be made while the apparatus is assembled and under pressure. There are two small glass windows in the wall of the chamber.

High voltage is supplied to the test gap within the pressure chamber from either of two transformers, one rated 110 to 33,000 volts, 15 kva, and the other 220 to 300,000 volts, 300 kva. The latter transformer is equipped with a tertiary voltmeter winding, which is used for voltage measurement. When the 33 kv transformer is used, voltage is measured across the primary winding and the output voltage is obtained by means of the transformer turn ratio. A crest voltmeter is

Paper 41-21, recommended by the AIEE committee on basic sciences and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 6, 1940; made available for preprinting December 3, 1940.

H. H. SKILLING is associate professor of electrical engineering, Stanford University, Calif.; W. C. BRENNER, recently a graduate student in electrical engineering at Stanford University, is student engineer with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

The authors wish to acknowledge the co-operation of the International Telephone and Telegraph Company in making possible the research leading to this paper.

1. For all numbered references, see list at end of paper.

---

steel. Consequently noise can be reduced by proper selection of the steel.

Conclusions

1. Transformer noise originates principally in the magnetostriction of the core iron.

2. Transformer noise can be calculated from the design constants using as a base magnetostriction tests of the core iron and the other relations given.

3. The most effective methods of reducing basic transformer noise are by reducing the induction in the iron or by reducing the magnetostriction of the iron.

4. The sound intensity produced by similar transformers with the same induction in the core, varies as the two-thirds power of the weight.

5. The sound intensity produced by a transformer with core iron having normal magnetostriction varies as the square of the magnetostriction. This relation can be used to compare the sound intensities produced at various inductions or to compare the sound levels of various core steels.

used for all measurements to eliminate error resulting from nonsinusoidal wave form. The over-all accuracy of voltage measurement was checked by comparison of measured values of sparking voltage between 20-millimeter spheres with AIEE standard values; the difference was less than 0.5 kv up to a reading of 40 kv, the highest voltage compared.

Resistance is used in the high-voltage connection to limit current in the test gap to one-half ampere. When sparking occurs the flow of current is interrupted at the end of the first quarter-cycle of 60-cycle current by a high-speed circuit breaker in the transformer primary circuit.

Voltage is continuously adjustable over the entire range of the transformers by means of a tap-changing transformer and an induction-type voltage regulator in the transformer primary circuit. During certain tests the transformer power is supplied from a synchronous sine-wave motor-generator set; in this case it is possible to adjust voltage by changing the generator field current as well as by means of the transformer and regulator.

Procedure

A generally uniform method of testing for the sparking voltage was followed. The spheres between which sparking was to take place were mounted in the micrometer head within the pressure chamber after having been cleaned and polished. Various methods of polishing were used, and no difference was found between polishing with rouge or metal polish, by hand or by motor-driven buffing wheel. In one case a motor-driven wire brush was used on steel spheres, and although it altered the appearance from a mirror surface to a matte surface it had no effect on the electrical behavior. The presence of an oil film on the spheres made no apparent difference in sparking voltage; however it is difficult to be sure that in any case the spheres were entirely free from oil because of the probability of oil being carried into the test chamber from either an air compressor or a storage cylinder.

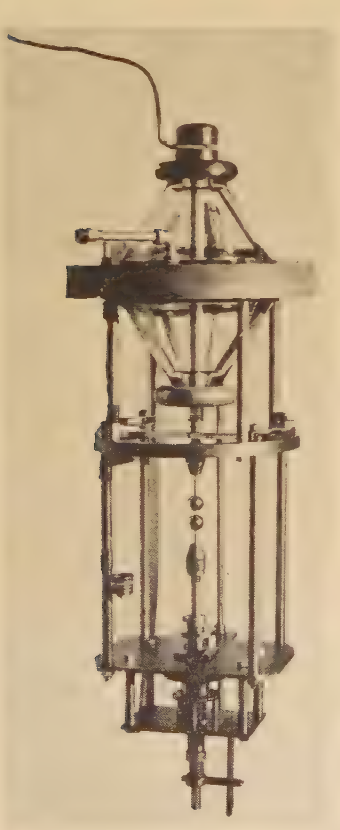


Figure 1. The sphere spark gap and supporting framework

Figure 2. The test chamber containing air under pressure

When an air compressor was used the air was cooled and filtered before being admitted to the test chamber. Despite the filtering, particles of oil of extremely small size were carried into the test chamber. Although the presence of the resulting haze of oil particles within the chamber had no noticeable effect on the sparking voltage, its presence resulted in a black oily deposit on the sphere surfaces after continued sparking. This was avoided by compressing the air several hours before it was used, thereby allowing the oil particles to settle out; when this procedure was followed the compressed air was perfectly clear and free from haze.

Before measuring sparking voltage the gap was adjusted to the desired length. A zero setting of the micrometer was obtained by means of a neon glow lamp, as described above. The micrometer setting was read when the lamp lighted as the spheres were being brought together and when it went out as they were separated. The difference between the two readings was normally less than 0.0001 inch.

Sixty-cycle voltage was applied to the gap, and the voltage was raised gradually until a spark occurred. The time required to raise voltage to sparking value varied from a few seconds to about half a minute, and sometimes was extended over several minutes. In some cases the speed of application of voltage was an important factor, as will be discussed.

At each particular spacing and pressure a number of readings of sparking voltage were measured and recorded. The number of readings depended upon circumstances, and particularly upon the uniformity of the measurements. If the first eight or ten sparks were at substantially the same voltage (within two or three per cent) they were considered satisfactory, but if there were radical variations the test was continued until 20, or 40, or as many as 100 sparking voltages were recorded. Either the pressure or the spacing was then changed and another series of readings was made.

Several series of tests were made with a quartz-tube mercury-arc lamp so located within the pressure chamber that its light fell on the spheres and passed through the gap between the spheres. It is impossible to say that its presence made any significant difference in the results, either in the value of voltage or in consistency of results. Use of the lamp was not continued.

Interpretation of Data

An *average* of the several voltage readings at any given spacing and pressure is not adequate to represent the results. There is apparent in much of the data a distinct trend:[6] the first sparking voltages are low and succeeding ones are higher in such a way that they appear to approach a limit. After four or five sparking voltages have been measured in rapid succession (less than a minute apart) the value of sparking voltage becomes stabilized. There is frequently a gradual rise of ten per cent or more in sparking voltage from the first spark to the fourth or fifth, while random variations of sparking voltage thereafter are not likely to vary more than one or two per cent from the trend value. If the series of sparking measurements is interrupted for five or ten minutes, however,

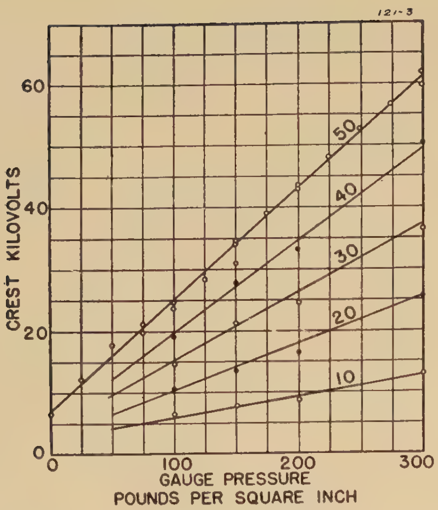


Figure 3. Sparking in air between brass spheres. Spark gap length as noted on curves in thousandths of an inch

and is then recommenced, it is probable that the first few sparks after interruption will occur at slightly reduced voltage and the stabilized value will have to be re-established. Occasionally, also, there is a break from the stabilized sparking voltage for no apparent reason; a spark will occur several per cent below the trend voltage, and successive sparks will be consecutively higher until the stabilized value is again reached.

An upward trend at the beginning of a series of sparks was found in most voltage measurements in which the voltage was greater than about 30 kv; that is, in case of either high pressure or relatively long spark gap. There was no such trend observed at atmospheric pressure, or in most measurements below about 20 kv. Under no circumstances was there any appearance of a downward trend; the voltage readings were either quite consistent or else the erratic readings were below the stabilized value. The amount of variation between the stabilized value of voltage and the lowest sparking voltages was of the order of magnitude of ten per cent.

The stabilized value of voltage is reproducible from time to time; an average voltage value, on the other hand, cannot readily be repeated and is not particularly significant because it depends on the number of measurements at a given setting of the gap and on the history of sparking of the gap. Therefore the stabilized value of voltage has been accepted as the best value to use in representing test results in this paper. It must be recognized that a reasonable engineering value of sparking voltage is about ten per cent below the values here given because of the likelihood of occasional sparks at voltages below the stabilized value.

To a slight extent the sparking voltage at high pressure was dependent upon time of application of voltage. The stable trend value was found by raising voltage at such a rate that sparks were produced at the rate of one or two per minute. If, after the stable condition had been established, voltage two or three per cent lower than the stable sparking value was applied continuously, sparking would usually occur after some time. The time that elapsed before sparking in such a case might be from a few seconds to ten minutes. If the applied voltage was as much as five per cent below the trend value, sparking might be delayed 30 minutes. Applied voltages ten per cent or more below the trend value did not produce sparking regardless of time. To insure steady voltage supply for these tests, power was taken from a motor-generator set.

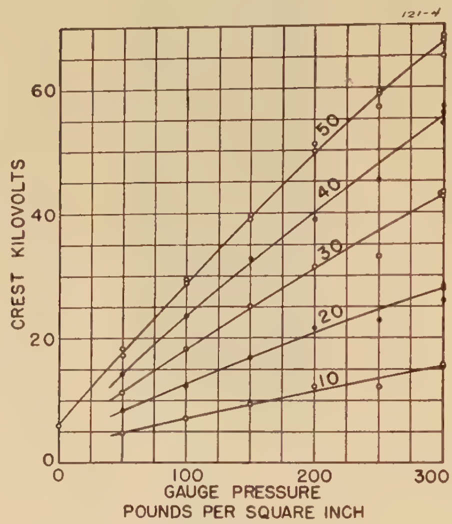


Figure 4. Sparking in air between steel spheres. Spark gap length as noted on curves in thousandths of an inch

It is believed that the rising trend of sparking voltage and the time lag of sparking are associated phenomena, for they appeared under the same conditions.

Results

Results are shown in figures 3 and 4. Each indicated point represents a stabilized value determined from a series of individual voltage readings. About 2,000 individual readings of sparking voltage are represented by these sets of curves.

The data of figure 4 may be presented in another form which is more compact, although less convenient for reference. This is done by plotting the sparking voltage as a function of the product of the independent variables, pressure, and spacing between electrodes. This product may be designated PS; the pressure P is most conveniently measured in atmospheres, and the spacing between electrodes, S, may be in inches.

According to the law for sparking commonly known as Paschen's law[3,4,5], voltage at breakdown should be a function of the product PS. Numerically, Paschen's law may be expressed[3] in the above units as

$$V=75.4PS+1.7 \text{ kilovolts} \tag{1}$$

If Paschen's law could be extrapolated from the low pressure range, below one atmosphere, for which it was determined, to cover the many-times greater range up to 21 atmospheres, the experimental points from figure 3 should all lie on a single straight line when plotted against the product PS. That this is approximately true may be seen in figure 5, in which all experimental points could be represented by a single straight line with an error not exceeding ten per cent. There is, however, a consistent deviation that corresponds to the drooping curvature of the lines of figure 3, and sparking voltages at high pressure are lower than sparking voltages for the same value of PS at low pressure.

In earlier papers[1] it has been suggested that this systematic deviation might result from field emission; that is, it might be caused by electrons drawn from the cathode by the extremely high electric field at the cathode surface. If this is so the deviation from Paschen's law could reasonably be expected to be a function of the electric field strength.[2] Inspection of figure 5 suggests the following modified expression for sparking voltage, in which V/S is the electric field strength between electrodes, and a is a coefficient to be determined from the data:

$$V=76.0PS(1-aV/S)+1.7 \text{ kilovolts} \tag{2}$$

Solving for sparking voltage, discarding a term of negligible importance, and evaluating the coefficient a, one obtains:

$$V=\frac{76.0PS}{1+0.009P}+1.7 \text{ kilovolts} \tag{3}$$

The coefficient has here been evaluated to make equation 3 agree with experimental results obtained with *brass* electrodes. The pressure P is in atmospheres and the spacing S in inches.

It may be seen that results obtained with steel electrodes (figure 4) differ slightly from results with brass electrodes (figure 3). Sparking voltages at pressures less than about 50 pounds per square

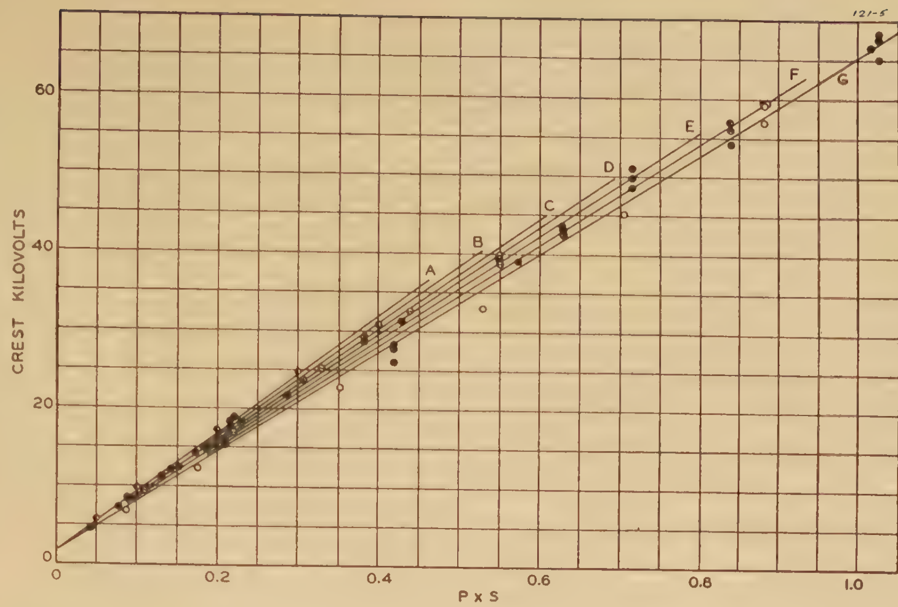


Figure 5. Sparking in air between brass spheres

P, absolute air pressure in atmospheres; *S*, spark gap length in inches. Points shown are experimental, lines are computed from equation 3

Line *A* and points marked ◐ are for 0 pounds per square inch pressure

Line *B* and points marked ⊕ are for 50 pounds per square inch pressure

Line *C* and points marked ⊙ are for 100 pounds per square inch pressure

Line *D* and points marked ⊖ are for 150 pounds per square inch pressure

Line *E* and points marked ● are for 200 pounds per square inch pressure

Line *F* and points marked ○ are for 250 pounds per square inch pressure

Line *G* and points marked ⊗ are for 300 pounds per square inch pressure

inch are the same for steel and brass, and both agree with Paschen's law. At higher pressures the deviation from Paschen's law is greater for steel than for brass. If the deviation is assumed to be a result of field emission, it is not surprising that it should be different with different electrode materials. A difference between sparking voltage with iron and copper electrodes was noted in an earlier paper by one of the authors;[1] although it was not at that time known to be significant, it now appears comparable to the difference between steel and brass shown by figures 3 and 4.

Values of sparking voltage were measured between aluminum spheres, also. Results using aluminum electrodes in air were inclined to be erratic, some sparking voltages being as high as the values obtained with brass spheres while others were lower than results with steel. Repeated sparking between aluminum spheres in air tended to reduce the sparking voltage, the inference being that a chemical change of the electrode surfaces was taking place. (Aluminum electrodes give consistent results, comparable with brass electrodes, when used in nitrogen.)

To describe results obtained with *steel* electrodes an expression of the form of equation 3 may be used:

$$V=\frac{76.0PS}{1+0.019P}+1.7 \text{ kilovolts} \qquad (4)$$

The coefficient in the denominator is here adjusted to give as good agreement as possible with the data of figure 4; agreement is within about ten per cent.

Although this expression for steel electrodes was derived to fit the experimental results obtained by the authors, it gives excellent agreement with sparking voltages measured by A. H. Howell.[5] Howell's electrodes were "turned from ordinary cold rolled steel." His results, although obtained with direct current from a Van de Graaff generator, appear to extend the range of equation 4 to pressures as high as 600 pounds per square inch and values of the product *PS* as great as ten.

Equation 4 also gives reasonably good agreement with results obtained by R. C. Buehl[6] with 60-cycle alternating voltage in nitrogen up to pressures of 140 atmospheres (2,060 pounds per square inch) and *PS* of seven. Agreement is within ten per cent for most of Buehl's data.

It is, furthermore, evident that Paschen's law may be considered a special case of equations 3 or 4 that applies with good accuracy when the air pressure is below about five atmospheres. Since Paschen's law has been experimentally substantiated for values of *PS* as low as 0.05 for pressures below atmospheric, it follows that equations 3 and 4 are accurate in that region also.

These considerations indicate the useful range of application of equations 3 and 4.

References

1. The Electric Strength of Air at High Pressure, H. H. Skilling. AIEE Transactions, volume 58, 1939 (Apil section), pages 161–5.

2. Discussion of reference 1 by D. W. Ver Planck.

3. Electricity in Gases, J. S. Townsend. Oxford Press, London, 1915.

4. Fundamental Processes of Electrical Discharge in Gases, L. B. Loeb. John Wiley and Sons, New York, 1939.

5. Breakdown Studies in Compressed Gases, A. H. Howell. AIEE Transactions, volume 58, 1939 (May section), pages 193–204.

6. Discussion of reference 5 by R. C. Buehl.

See references 1 and 5 for complete bibliography.

Negative Damping of Electrical Machinery

C. CONCORDIA
MEMBER AIEE

G. K. CARTER
ASSOCIATE AIEE

Synopsis: This paper presents (1) a more nearly complete and exact criterion of instability or hunting of a synchronous machine as influenced by its armature or tie line resistance, (2) a general stability criterion which includes in one formula three previously separately treated cases: the usual steady state power limit, rotor hunting produced by armature resistance, and self-excitation produced by series capacitance in the armature circuit, and (3) an indication, by means of a numerical example, of the limitations of the previously used approximate criterion for hunting due to armature resistance.

IN PREVIOUS treatments, hunting, self-excitation, and loss of synchronism have been considered only separately, neglecting their mutual interactions. The present paper, on the other hand, considers their mutual effects and thus provides a general analysis by reference to which the limitations and proper fields of application of the approximate formulas may be found. Application of the complete criterion given is however rather laborious, and it is not suggested for general use in place of the approximate forms.

Introduction

When synchronous machines are tied together through impedances having rather high resistance components, and when there is insufficient rotor damping, the machines tend to hunt. Also, when a machine is connected to a capacitance load or to a system through a series capacitor there is exhibited under certain conditions a tendency to self-excite. Both of these phenomena have been treated extensively in electrical engineering literature, and the conditions under which one or the other form of operation is to be expected are reasonably well known. However, the two phenomena have so far been considered only separately, e.g., the first in references 1, 2, 3, and the second in references 3, 4, 5, 6, 7, among many others. It was pointed out in reference 3 that the two phenomena were basically the same and could be treated as two aspects or special cases of a single, more general characteristic. That is, a more exact consideration of the equations of motion of electrical machinery shows that in general the two phenomena are mutually dependent and in fact inseparable, and that it is only because of the relatively large differences in the orders of magnitudes of the principal controlling features of each that they can be approximately separated. Since all previous treatments have considered them separately and have consequently neglected their mutual interactions, it was felt that an investigation should be made to find out just what these interactions might be. The results of such an investigation, comprising a quantitative study of the complete equations of motion of a simple electromechanical system, are presented in this paper.

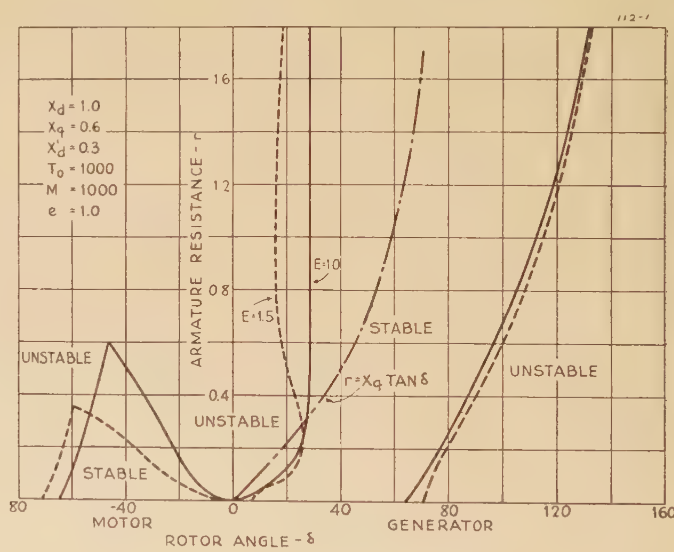
Preliminary Considerations

Before proceeding to the combining of self-excitation and hunting into a single form (here called negative damping), the simpler case of a system which can show only hunting was first studied, since it has been found that the behavior of this system according to the equations used here is somewhat different from that according to the approximate criteria previously given.[1]

A single synchronous machine with only one rotor winding, connected to an infinite bus, may become unstable at small generator angles or at any motor angle if the armature resistance is too high, and at large generator angles if the armature resistance is too low. Both concepts are well known, but the latter may be amplified by pointing out that at large generator angles and high resistances the system, although stable, has only a negligible synchronizing torque and load capacity.

Figures 1 and 2 show the results of stability calculations made for this case. The regions of stable operation were determined by the application of Routh's[11] stability criterion to equation 6 of the appendix. Figure 1 is for comparatively low values of armature resistance; in this figure, the solid line represents the stability limit for unit field excitation, the dashed line that for one and a half times unit excitation. For comparison, the hunting criterion $r \leq x_q \tan \delta$, of reference 1, is also shown, as a dot-and-dash line for generator angles.

Figure 1. Synchronous machine connected to infinite bus—stability limits—effect of armature resistance r and field excitation E



It is seen that the approximate criterion is optimistic for small angles and pessimistic for larger generator angles; for the larger motor angles (from about 30 degrees to the steady state boundary) the approximate criterion $r = x_q \tan \delta$ agrees fairly closely with the more nearly exact criterion used here. At light loads figure 1 indicates that $r \leq x_d' \tan \delta$ would be a

Paper 41-12, recommended by the AIEE committees on power transmission and distribution, and electrical machinery, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted October 11, 1940; made available for preprinting November 26, 1940.

C. CONCORDIA is engineer, central station department, General Electric Company, Schenectady, N. Y.; G. K. CARTER is in the engineering general department of the same company.

1. For all numbered references, see list at end of paper.

better criterion of stability than $r \leq x_q \tan \delta$, at least for the value of field time constant $T_0=1{,}000$ studied. The more nearly exact criterion shows no instability due to high armature resistance for generator angles of more than about 30 degrees. This is not in conflict with experience, since those cases of hunting which have actually been encountered have usually occurred only at light load. Another check is obtained by noting that the amount of armature resistance required to produce negative damping at light loads decreases as the field excitation is increased, which is consistent with the observation that the severity of hunting is usually increased by increased excitation. The outer boundaries of figure 1 are found to check the steady state stability limits determined by the usual steady state power-angle relations.[12]

Figure 2 is of only theoretical interest, as the resistances involved are so high that the machine armature is practically open circuited.

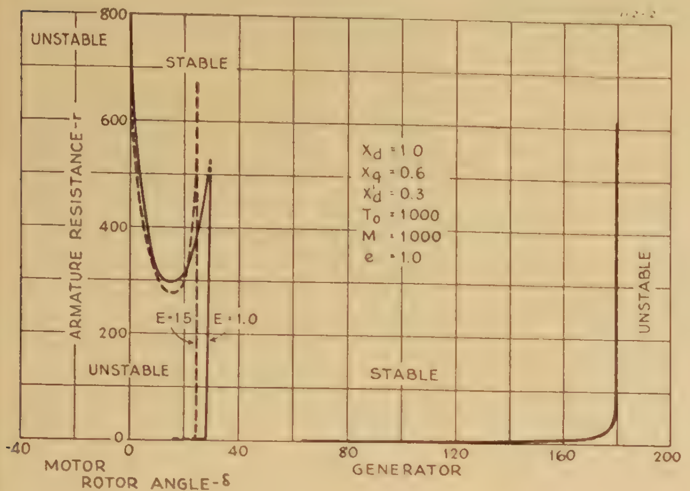


Figure 2. Synchronous machine connected to infinite bus—stability limits—effect of armature resistance r and field excitation E at high values of r

Negative Damping With Series Capacitors

Figure 3 shows some of the results of stability calculations made for the general case of a synchronous machine connected to a bus through a series capacitor. Equation 4 of the appendix gives the equation for this case. In a general way the correspondence of this stability boundary to those which would be obtained by the previous approximate methods is that first, the left hand rising portion of the curve corresponds roughly to the lower portion of the curve for $M=\infty$ of figure 1, reference 5, and second, the right hand decreasing portion corresponds to the boundary which would be found by application of the approximate criterion for hunting if the capacitive reactance x_c is subtracted from the quadrature axis reactance x_q to form an effective net reactance. As in the previous section, the criterion $r \leq (x_d' - x_c) \tan \delta$ (shown in the figure by a dashed line) forms a better, in fact a rather good, criterion.

Figure 3 indicates that instability may occur if the resistance is too small and if the resistance is too large. An amortisseur on the machine rotor will increase the maximum allowable armature resistance so much as practically to remove any upper (right hand in figure 3) boundary. On the other hand the allowable minimum resistance will also be increased, as indicated by figure 4. Figure 4 has been calculated by the equations of reference 5, and may be compared to figure 1, reference 5, to show the effect of the amortisseur. The fact that an amortisseur does not tend to suppress the negative damping introduced by series capacitance need not be alarming however, as figure 5 shows that resistance in shunt with the capacitor is still effective in preventing the instability, just as was found in reference 3, figure 18. Figure 5 was calculated from equation $1d$ of reference 3, using an extension of equations $2d$ and $3d$ to include the amortisseur.[10]

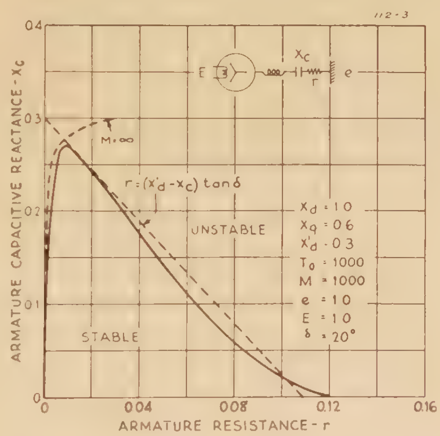


Figure 3. Synchronous machine connected to infinite bus through armature series capacitance—stability limits at rotor angle $\delta=20$ degrees

Conclusions

1. A more complete and exact criterion of instability of a synchronous machine as influenced by armature resistance has been derived by application of Routh's test to the system performance equations.

2. A general criterion of instability has been derived which includes three previously separately treated cases: the normal steady state power limit, rotor hunting produced by armature resistance, and self-excitation produced by series capacitance in the armature circuit.

3. The limitations of the previously used approximate criterion for hunting due to armature resistance have been determined.

4. The effect on the stability limit of series capacitance in the armature circuit has been studied by the more complete criterion and shown to agree fairly well with the approximate criteria for appropriate limiting conditions.

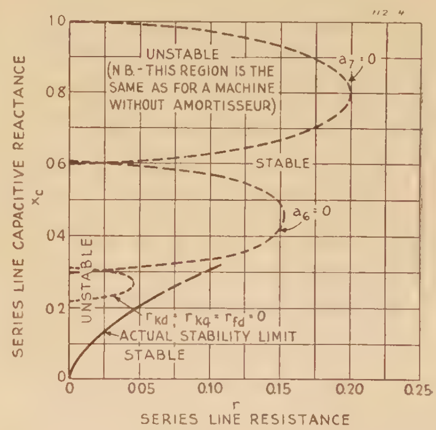


Figure 4. Negative damping of synchronous machines with series capacitors—effect of amortisseur. Series resistance required for stable operation

$x_d=1.0$ $x_d'=0.3$ $x_d''=0.218$
$r_{kd}=0.02$ $T_0=1{,}000, \omega=1.0, \alpha=0$
$x_q=0.6$ $x_q''=0.311$ $r_{kq}=0.04$
($a_7=0$, $a_6=0$, etc., are approximate criteria)

Appendix

Nomenclature

r = armature circuit resistance
δ = angle between rotor axis and axis of stator voltage

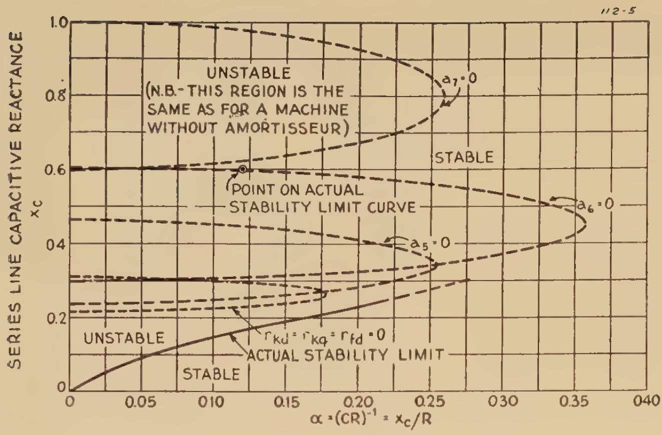


Figure 5. Negative damping of synchronous machines with series capacitors—effect of amortisseur. Shunt resistance required for stable operation

$x_d = 1.0$ $\quad x_d' = 0.3$ $\quad x_d'' = 0.218$
$r_{kd} = 0.02$ $\quad T_0 = 1{,}000,\ \omega = 1.0,\ r = 0$
$x_q = 0.6$ $\quad x_q'' = 0.311$ $\quad r_{kq} = 0.04$
($a_7 = 0$, $a_6 = 0$, etc., are approximate criteria)

x_d = direct axis synchronous reactance
x_q = quadrature axis synchronous reactance
x_d' = direct axis transient reactance
x_d'' = direct axis subtransient reactance
x_q'' = quadrature axis subtransient reactance
T_0 = field open circuit time constant
x_c = armature circuit capacitive reactance
R = resistance in parallel with x_c
$\alpha = x_c/R$
M = rotor inertia factor in radians
e = stator voltage
i = stator current
ψ = stator flux linkages
(subscripts d and q indicate direct and quadrature axis components, respectively)
θ = rotor angle in electrical radians
p = time derivative operator $= d/dt$
$(p\theta) = \omega$ = rotor angular velocity
T = mechanical torque input to rotor
E = field excitation voltage
$G(p)$ = mutual impedance operator giving armature flux linkages in terms of field excitation
$x_d(p)$ = armature direct axis operational impedance
$x_q(p)$ = armature quadrature axis operational impedance
a_7, a_6 = the coefficients of p^0, p^1, respectively, in the operational common denominators used in the calculations of figures 4 and 5

Analysis

In this appendix the equations of a synchronous or induction machine with a capacitor and resistor in parallel in the armature circuit are extended to include the effect of rotor inertia during small changes (e.g., oscillations) of rotor speed. The fundamental equations for this case have been derived in references 5, 8, and 9, and are:

$$\left.\begin{aligned}
&(p+\alpha)[e_d - p\psi_d + ri_d + \psi_q(p\theta)] + x_c i_d - \\
&\qquad (p\theta)[e_q - p\psi_q + ri_q - \psi_d(p\theta)] = 0 \\
&(p+\alpha)[e_q - p\psi_q + ri_q - \psi_d(p\theta)] + x_c i_q + \\
&\qquad (p\theta)[e_d - p\psi_d + ri_d + \psi_q(p\theta)] = 0 \\
&T = \psi_d i_q - \psi_q i_d + Mp^2\theta
\end{aligned}\right\} \quad (1)$$

where

$e_d = e \sin\delta \qquad \psi_d = G(p)E - x_d(p)i_d$
$e_q = e \cos\delta \qquad \psi_q = -x_q(p)i_q$

and the other symbols are as defined in reference 8 and in the nomenclature. From equations 1, by taking small changes in e, E, i_d, i_q, and $\delta(\Delta\theta = \Delta\delta)$, one may obtain:

$$\left.\begin{aligned}
&[(p+\alpha)(px_d(p)+r) + x_c - \omega_0^2 x_d(p)] \times \\
&\Delta i_d - [(p+\alpha)\omega_0 x_q(p) + \omega_0(px_q(p)+r)] \times \\
&\Delta i_q + \{[(p+\alpha)\psi_{q0} + 2\omega_0\psi_{d0} - e_{q0} - ri_{q0}] \times \\
&p + (p+\alpha)e_{q0} + \omega_0 e_{d0}\}\,\Delta\delta = [-(p+\alpha) \times \\
&\sin\delta_0 + \omega_0\cos\delta_0]\,\Delta e + [(p+\alpha)p - \omega_0^2] \times \\
&\qquad\qquad G(p)\,\Delta E \\
&[(p+\alpha)\omega_0 x_d(p) + \omega_0(px_d(p)+r)]\,\Delta i_d + \\
&[(p+\alpha)(px_q(p)+r) + x_c - \omega_0^2 x_q(p)]\,\Delta i_q + \\
&\{[-(p+\alpha)\psi_{d0} + 2\omega_0\psi_{q0} + e_{d0} + ri_{d0}]p - \\
&(p+\alpha)e_{d0} + \omega_0 e_{q0}\}\,\Delta\delta = [-(p+\alpha)\cos\delta_0 - \\
&\omega_0\sin\delta_0]\,\Delta e + (2p+\alpha)\omega_0 G(p)\,\Delta E \\
&-[\psi_{q0} + i_{q0}x_d(p)]\,\Delta i_d + [\psi_{d0} + i_{d0}x_q(p)] \times \\
&\qquad \Delta i_q + Mp^2\,\Delta\delta = \Delta T - i_{q0}G(p)\,\Delta E
\end{aligned}\right\} \quad (2)$$

where $\omega_0 = (p\theta)_0 = 1.0$, and the steady state quantities ψ_{d0}, ψ_{q0}, i_{d0}, i_{q0} are found as described in reference 5, equations 32, 33, 34.

The stability or instability of the system may now be determined from the p roots of the common denominator of the dependent variables Δi_d, Δi_q, and $\Delta\delta$ in equations 2. If the real part of any one of these roots is positive, the system is unstable. The roots themselves need not be found; it is only necessary to test the expression by Routh's stability criterion.[11]

The common denominator is the determinant of the coefficients of the dependent variables in equations (2), and is equal to:

$$\begin{aligned}
D = {} & \{[(p+\alpha)(px_d(p)+r) + x_c - \omega_0^2 x_d(p)] \times \\
& [(p+\alpha)(px_q(p)+r) + x_c - \omega_0^2 x_q(p)] + \\
& [(p+\alpha)\omega_0 x_d(p) + \omega_0(px_d(p)+r)] \times \\
& [(p+\alpha)\omega_0 x_q(p) + \omega_0(px_q(p)+r)]\}\,Mp^2 + \\
& \llbracket\{[(p+\alpha)\psi_{q0} + 2\omega_0\psi_{d0} - e_{q0} - ri_{q0}]p + \\
& (p+\alpha)e_{q0} + \omega_0 e_{d0}\}[(p+\alpha)\omega_0 x_d(p) + \\
& \omega_0(px_d(p)+r)] - \{[-(p+\alpha)\psi_{d0} + \\
& 2\omega_0\psi_{q0} + e_{d0} + ri_{d0}]p - (p+\alpha)e_{d0} + \\
& \omega_0 e_{q0}\}[(p+\alpha)(px_d(p)+r) + \\
& x_c - \omega_0^2 x_d(p)]\rrbracket[\psi_{d0} + i_{d0}x_q(p)] + \\
& \llbracket[(p+\alpha)\omega_0 x_q(p) + \omega_0(px_q(p)+r)] \times \\
& \{[-(p+\alpha)\psi_{d0} + 2\omega_0\psi_{q0} + e_{d0} + ri_{d0}]p - \\
& (p+\alpha)e_{d0} + \omega_0 e_{q0}\} + [(p+\alpha)(px_q(p)+r) + \\
& x_c - \omega_0^2 x_q(p)]\{[(p+\alpha)\psi_{q0} + 2\omega_0\psi_{d0} - \\
& e_{q0} - ri_{q0}]p + (p+\alpha)e_{q0} + \omega_0 e_{d0}\}\rrbracket \times \\
& [\psi_{q0} + i_{q0}x_d(p)] \qquad (3)
\end{aligned}$$

With $M = \infty$, equation 3 reduces to that for the previously treated case of constant rotor speed (reference 3, appendix D). Also if the machine is initially unexcited, so that $\psi_0 = i_0 = 0$, the regions of stable operation are the same as before. In the general case, however, the performance will be affected by the operating angle, machine inertia, and excitations.

For a machine with only one rotor winding, $x_d(p) = (x_d'T_0p + x_d)/(T_0p+1)$ and $x_q(p) = x_q$ (see reference 8), and equation 3 may be expanded in powers of p to become:

$$\begin{aligned}
D' = {} & \{p^5 x_q x_d' T_0 + p^4[x_q x_d + rT_0(x_q + x_d') + \\
& 2\alpha T_0 x_q x_d'] + p^3[(2x_q x_d' + x_c(x_q + x_d'))T_0 + \\
& r(x_d + x_q + rT_0) + \alpha(2x_d x_q + \alpha x_q x_d' T_0) + \\
& 2\alpha r T_0(x_q + x_d')] + p^2[2x_d x_q + x_c(x_d + x_q) + \\
& r(T_0(2x_c + x_q + x_d') + r) + \alpha(T_0 x_c(x_q + x_d') + \\
& 2T_0 x_q x_d' + \alpha x_d x_q) + \alpha r(2x_d + 2x_q + 2T_0 r + \\
& T_0\alpha(x_q + x_d'))] + p[T_0(x_c - x_q)(x_c - x_d') + \\
& r(x_d + x_q + 2x_c + rT_0) + \alpha(x_c(x_d + x_q) + \\
& 2x_d x_q + \alpha x_q x_d' T_0) + \alpha r(2x_c T_0 + 2r + \\
& \alpha(x_d + x_q) + \alpha r T_0)] + [(x_d - x_c)(x_q - x_c) + \\
& r^2 + \alpha^2 x_d x_q + 2\alpha r x_c + (\alpha r)^2]\}\,Mp^2 + \\
& (\psi_{d0} + i_{d0}x_q)\{p^5(x_d' T_0 \psi_{d0}) + p^4[-x_d' T_0 \times \\
& (-\alpha\psi_{d0} + 2\psi_{q0} + ri_{d0}) + (x_d + \alpha x_d' T_0 + rT_0) \times \\
& \psi_{d0} + 2x_d' T_0 \psi_{q0}] + p^3[x_d' T_0(\alpha e_{d0} - e_{q0}) - \\
& (x_d + \alpha x_d' T_0 + rT_0)(-\alpha\psi_{d0} + 2\psi_{q0} + ri_{d0}) + \\
& (\alpha x_d + r + \alpha r T_0 - x_d' T_0 + x_c T_0)\psi_{d0} + \\
& 2x_d' T_0(\alpha\psi_{q0} + 2\psi_{d0} - ri_{q0}) + (2x_d + rT_0 + \\
& \alpha x_d' T_0)\psi_{q0}] + p^2[(x_d + \alpha x_d' T_0 + rT_0)(\alpha e_{d0} - \\
& e_{q0}) + (2x_d + rT_0 + \alpha x_d' T_0)(\alpha\psi_{q0} + 2\psi_{d0} - \\
& ri_{q0}) - (\alpha x_d + r + \alpha r T_0 - x_d' T_0 + x_c T_0) \times \\
& (-\alpha\psi_{d0} + 2\psi_{q0} + ri_{d0}) + (r + \alpha x_d)\psi_{q0} + (x_c - \\
& x_d + \alpha r)\psi_{d0} + 2x_d' T_0(\alpha e_{q0} + e_{d0})] + p[(\alpha x_d + \\
& r + \alpha r T_0 - x_d' T_0 + x_c T_0)(\alpha e_{d0} - e_{q0}) + (2x_d + \\
& rT_0 + \alpha x_d' T_0)(\alpha e_{q0} + e_{d0}) - (x_c - x_d + \alpha r) \times \\
& (-\alpha\psi_{d0} + 2\psi_{q0} + ri_{d0}) + (r + \alpha x_d) \times \\
& (\alpha\psi_{q0} + 2\psi_{d0} - ri_{q0})] + [(x_c - x_d + \alpha r) \times \\
& (\alpha e_{d0} - e_{q0}) + (r + \alpha x_d)(\alpha e_{q0} + e_{d0})]\} + \\
& [(\psi_{q0} T_0 + i_{q0} x_d' T_0)p + (\psi_{q0} + i_{q0} x_d)] \times \\
& \{p^4(\psi_{q0} x_q) + p^3[\psi_{q0}(\alpha x_q + r) + (\alpha\psi_{q0} + \\
& 2\psi_{d0} - ri_{q0})x_q - \psi_{d0} 2x_q] + p^2[\psi_{q0}(r\alpha + \\
& x_c - x_q) + (\alpha\psi_{q0} + 2\psi_{d0} - ri_{q0})(\alpha x_q + r) + \\
& (\alpha e_{q0} + e_{d0})x_q - \psi_{d0}(\alpha x_q + r) + (-\alpha\psi_{d0} + \\
& 2\psi_{q0} + ri_{d0})2x_q] + p[(\alpha\psi_{q0} + 2\psi_{d0} - ri_{q0}) \times \\
& (r\alpha + x_c - x_q) + (\alpha e_{q0} + e_{d0})(\alpha x_q + r) + \\
& (-\alpha\psi_{d0} + 2\psi_{q0} + ri_{d0})(\alpha x_q + r) - \\
& (\alpha e_{d0} - e_{q0})2x_q] + [(\alpha e_{q0} + e_{d0})(r\alpha + x_c - x_q) - \\
& (\alpha e_{d0} - e_{q0})(\alpha x_q + r)]\} \qquad (4)
\end{aligned}$$

Note that the coefficient of Mp^2 in this equation is the Δ' of equation $4d$, appendix D, of reference 3.

Equation 4 may be used to find the effect of rotor inertia on negative damping in the region of series capacitor applications where the machine is connected to an excited bus through a capacitor. For a capacitance load, as for transmission line capacitance, e_{d0} and e_{q0} should be taken as zero, in which case the effect of rotor oscillations on the borderline of stability is believed to be negligible, as there are no synchronizing torques.

For the special case of no armature circuit capacitance ($x_c = 0$ or $\alpha = \infty$), the performance equations 2 become

$$\left.\begin{aligned}
&-(px_d(p)+r)\,\Delta i_d + \omega_0 x_q(p)\,\Delta i_q - \\
&\qquad (\psi_{q0}p + e_{q0})\,\Delta\delta = \sin\delta_0\,\Delta e - pG(p)\,\Delta E \\
&-\omega_0 x_d(p)\,\Delta i_d - (px_q(p)+r)\,\Delta i_q + \\
&(\psi_{d0}p + e_{d0})\,\Delta\delta = +\cos\delta_0\,\Delta e - \omega_0 G(p)\,\Delta E \\
&-(\psi_{q0} + i_{q0}x_d(p))\,\Delta i_d + (\psi_{d0} + i_{d0}x_q(p)) \times \\
&\qquad \Delta i_q + Mp^2\,\Delta\delta = \Delta T - i_{q0}G(p)\,\Delta E
\end{aligned}\right\} \quad (5)$$

Hollow Pipes of Relatively Small Dimensions

W. L. BARROW
MEMBER AIEE

H. SCHAEVITZ
ASSOCIATE AIEE

Summary

SEVERAL cross sectional shapes for hollow-pipe transmission lines are described that provide lower operating frequencies for given outside dimensions than do the simple shapes heretofore proposed. The theory for one such line, the "septate coaxial cable" is derived, and experiments are reported. Cavity resonator embodying these principles are also described.

Introduction

The hollow-pipe type of conductor[1,2] for ultrahigh-frequency electromagnetic energy, although possessing several desirable features, has the disadvantage that its transverse dimensions are relatively large; namely, of magnitude comparable to the wave length. The object of this paper is to lessen this encumbrance by describing pipes that have transverse dimensions several times smaller than those of the simple forms previously proposed.*

The principle underlying the improved conductors derives from the properties of the $H_{0,1}$-waves[3] in a pipe of flat rectangular cross section, figure 1*A*. In this case, the critical wave length λ_0, i.e. the wave length above which no transmission takes place, is independent of d and depends on l only ($\lambda_0 = 2l$). By bending or folding the pipe transversely, keeping the separation between the top and bottom sides unchanged, a hollow conductor of smaller over-all dimensions may be obtained that has the same general internal configuration as the rectangular pipe. The deformation of the cross section may take place in a number of ways, several of which are shown in figure 1*B* to *D*. In the illustrations, the corresponding dimension l is indicated by a dotted line. In each of the deformed conductors there is a type of wave with a critical frequency approximately equal to $2l$, but the over-all dimensions of the deformed pipe are considerably smaller than those of 1*A* or of a circular pipe of the same critical value.

The conductor 1*B* may be thought of as a concentric line in which the center conductor is connected to and supported from the outer conductor along its entire length by a conducting radial rib or strip. Dielectric supports and spacers are unnecessary and the system is a uniconductor. Transmission in this particular example of the deformed pipes, which is here termed the *septate coaxial cable*, has been analyzed theoretically. Experiments have been made on it and on the partitioned rectangular type of 1*D*. The remainder of the paper presents the more important results of this research.

Theory of the Septate Coaxial Cable

The cylindrical co-ordinate system θ, r, x, in which x is the longitudinal co-ordinate, is indicated in figure 1*C*. A variation of all field components with the time t and with x of the form $e^{-hx+i\omega t}$ will be assumed, where h is the propagation constant, $\omega = 2\pi$ times frequency and $i = \sqrt{-1}$. The propagation constant for a pipe with a perfectly conducting wall is $i\beta$, where β is the phase constant. The attenuation constant α will not be given in this paper; although laborious, it may be calculated by known methods. The interior of the pipe has the dielectric constant ϵ, which is $10^{-11}/36\pi$ farads per centimeter for vacuum, air, and other gases that are primarily of interest for practical applications, and the permeability μ which is $4\pi \times 10^{-9}$ henries per centimeter for vacuum or gas.

The analysis begins with the wave equation in cylindrical co-ordinates, which is used to obtain solutions for the longitudinal field components E_x or H_x:

$$\left.\begin{matrix} E_x \\ H_x \end{matrix}\right\} = \sin(k\theta + C_3)\left\{C_1 J_k\left(r\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right) + C_2 Y_k\left(r\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)\right\} e^{-hx+i\omega t} \qquad (1)$$

J_k and Y_k are Bessel functions of first and second kind, respectively, and of order k; the constant $C_1, \ldots C_3$ and the quantities k and h are determined from

Paper 41-8, recommended by the AIEE committee on communication and presented at the AIEE winter convention, New York, N. Y., January 27–31, 1941. Manuscript submitted November 5, 1938; made available for preprinting November 4, 1940.

Much of the analytical and the experimental work of this paper was carried out in the Master's Thesis "Electromagnetic Waves in Longitudinally Partitioned Hollow Pipes," by H. Schaevitz, M.I.T., 1938.

W. L. BARROW is assistant professor of electrical communications, Massachusetts Institute of Technology, Cambridge, and H. SCHAEVITZ is junior electrical engineer, Philadelphia Navy Yard, Philadelphia, Pa.

1. For all numbered references, see list at end of paper.

* It is known that the dimensions of an ordinary hollow-pipe conductor may be reduced by filling its interior with a substance of dielectric constant substantially greater than unity. This method, however, introduces large losses because of the imperfectness of available dielectrics. The type of cables described herein accomplish the same result without incurring such dielectric losses. They will also effect a further reduction of dimensions in the dielectric filled pipes.

---

and equation 3 reduces to

$$\begin{aligned} D = Mp^2[(px_d(p)+r)(px_q(p)+r) + \\ \omega_0{}^2 x_q(p)x_d(p)] + (\psi_{d0} + i_{d0}x_q(p)) \times \\ [(px_d(p)+r)(\psi_{d0}p + e_{d0}) + \\ \omega_0 x_d(p)(\psi_{q0}p + e_{q0})] + (\psi_{q0} + i_{q0}x_d(p)) \times \\ [-\omega_0 x_q(p)(\psi_{d0}p + e_{d0}) + \\ (px_q(p)+r)(\psi_{q0}p + e_{q0})] \end{aligned} \qquad (6)$$

References

1. STABILITY OF SYNCHRONOUS MACHINES—EFFECT OF ARMATURE CIRCUIT RESISTANCE, C. A. Nickle and C. A. Pierce. AIEE TRANSACTIONS, volume 49, 1930, page 338.

2. EFFECT OF ARMATURE RESISTANCE UPON HUNTING OF SYNCHRONOUS MACHINES, C. F. Wagner. AIEE TRANSACTIONS, volume 49, 1930, page 1011.

3. ANALYSIS OF SERIES CAPACITOR APPLICATION PROBLEMS, J. W. Butler and C. Concordia. AIEE TRANSACTIONS, volume 56, 1937 (August section), page 975.

4. TRANSIENT PHENOMENA OF AN ALTERNATOR UPON CONDENSIVE LOAD, M. Takahashi. Researches of the Electrotechnical Laboratory, Tokyo, Japan, number 350, August 1933.

5. TWO-REACTION THEORY OF SYNCHRONOUS MACHINES, S. B. Crary. AIEE TRANSACTIONS, volume 56, 1937 (January section), pages 27–31.

6. Discussion of H. C. Stanley's paper "An Analysis of the Induction Machine," C. Concordia. AIEE TRANSACTIONS, volume 57, 1938, page 756.

7. TRANSIENT ANALYSIS OF ALTERNATING CURRENT MACHINERY, Y. H. Ku. *Journal of Electrical Engineering*, China, volume 3, number 4, August 1932, page 179.

8. TWO-REACTION THEORY OF SYNCHRONOUS MACHINES—GENERALIZED METHOD OF ANALYSIS—PART I, R. H. Park. AIEE TRANSACTIONS, volume 48, 1929, page 716.

9. TWO-REACTION THEORY OF SYNCHRONOUS MACHINES WITH ANY BALANCED TERMINAL IMPEDANCE, C. Concordia. AIEE TRANSACTIONS, volume 56, 1937 (September section), pages 1124–7.

10. THE OPERATIONAL IMPEDANCES OF A SYNCHRONOUS MACHINE, M. L. Waring and S. B. Crary. *General Electric Review*, volume 35, November 1932, pages 578–82.

11. ADVANCED RIGID DYNAMICS, E. J. Routh. Fourth edition, 1884, Macmillan and Company, New York, N. Y., page 170.

12. SYNCHRONOUS MACHINES II—STEADY-STATE POWER-ANGLE CHARACTERISTICS, R. E. Doherty and C. A. Nickle. AIEE TRANSACTIONS, volume 45, 1926, pages 927–42.

boundary conditions. The other components of field are obtained from (1) by means of Maxwell's equations. Two different kinds of solutions exist: one, in which $H_x=0$, corresponding to hollow-pipe waves of the E type; and the other, in which $E_x=0$, corresponding to hollow-pipe waves of the H type. In each instance, the boundary conditions for a perfectly conducting wall, i.e., the vanishing of the tangential component of electric field on all surfaces of the conductor, are next imposed on the solutions. A transcendental equation for the propagation constant h results, the solution for which allows the critical frequency, wave length and the other transmission properties to be calculated.

$E_{n,m}$-Waves

We place $H_x=0$ and derive the other field components from E_x in (1). The boundary condition requires $E_x=0$ for $\theta=0$, θ_0 and $r=a$, b. We find that $C_3=0$ and $k=n\pi/\theta_0$, where $n=1, 2 \ldots$ and that the field is given by:

$$\left.\begin{aligned}
E_x &= \sin k\theta\cdot G\cdot e^{-hx+i\omega t}\\
E_\theta &= \frac{-hk}{r\left[h^2+\left(\frac{\omega}{c}\right)^2\right]}\cos k\theta\cdot G\cdot e^{-hx+i\omega t}\\
E_r &= \frac{-h}{h^2+\left(\frac{\omega}{c}\right)^2}\sin k\theta\cdot\frac{dG}{dr}\cdot e^{-hx+i\omega t}\\
H_\theta &= \frac{i\omega\epsilon}{h^2+\left(\frac{\omega}{c}\right)^2}\sin k\theta\cdot\frac{dG}{dr}\cdot e^{-hx+i\omega t}\\
H_r &= \frac{i\omega\epsilon k}{r\left[h^2+\left(\frac{\omega}{c}\right)^2\right]}\cos k\theta\cdot G\cdot e^{-hx+i\omega t}\\
H_x &= 0\\
&\text{where}\\
G &= C_1J_k\left(r\sqrt{h_2+\left(\frac{\omega}{c}\right)^2}\right)+C_2Y_k\left(r\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)
\end{aligned}\right\}\quad(2)$$

The transcendental equation for h is:

$$\frac{J_k\left(a\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)}{Y_k\left(a\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)}=\frac{J_k\left(b\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)}{Y_k\left(b\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)}\quad(3)$$

This equation may be solved approximately by means of McMahon's series[4] to get β, where $h=i\beta$:

$$\beta=\sqrt{\left(\frac{\omega}{c}\right)^2-\left[\frac{m\pi}{b-a}+\frac{(4\pi^2n^2-\theta_0{}^2)(b-a)}{8abm\pi\theta_0{}^2}+\ldots\right]^2}\quad(4)$$

where $m=1, 2, 3\ldots.$

The critical frequency is the root of the equation $\beta=0$:

$$f_0=\frac{c}{2\pi}\left[\frac{m\pi}{b-a}+\frac{(4\pi^2n^2-\theta_0{}^2)(b-a)}{8abm\pi\theta_0{}^2}+\ldots\right]\quad(5)$$

The transmission characteristics may be found in the usual way: Wave length in pipe $=\lambda_p=\frac{2\pi}{\beta}$; phase velocity $=v_p=\frac{\omega}{\beta}$; group velocity $=v_g=\frac{d\omega}{d\beta}$.

In the septate coaxial cable, $\theta_0=2\pi$. For the special case of $n=1$, k becomes 1/2 and J_k and Y_k reduce to the following form:

$$\left.\begin{aligned}
J_{1/2}(x) &= \sqrt{\frac{2}{\pi x}}\sin x\\
Y_{1/2}(x) &= \sqrt{\frac{2}{\pi x}}\cos x\\
&\text{where}\\
x &= r\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}
\end{aligned}\right\}\quad(6)$$

Consequently, the phase constant becomes

$$\left.\begin{aligned}
\beta &= \sqrt{\left(\frac{\omega}{c}\right)^2-\left(\frac{m\pi}{b-a}\right)^2}\\
&\text{and}\\
\lambda_0 &= \frac{2(b-a)}{m}
\end{aligned}\right\}\quad(7)$$

For $m=1$, the critical wave length is equal to twice the radial distance between the outer and inner circular walls; this result bears a striking similarity to the $H_{1,0}$-wave in a rectangular pipe.

The electric intensity in the transverse cross section is given by:

$E_{1,m}$-Wave

$$\left.\begin{aligned}
E_r &= \frac{C_4}{\sqrt{r}}\sin\frac{\theta}{2}\left[\frac{m\pi}{b-a}\cos\left(\frac{m\pi}{b-a}r-C_5\right)-\frac{1}{2r}\sin\left(\frac{m}{b-a}r-C_5\right)\right]e^{-hx+i\omega t}\\
E_\theta &= \frac{C_4}{2r\sqrt{r}}\times\cos\frac{\theta}{2}\sin\left(\frac{m\pi}{b-a}r+C_5\right)e^{-hx+i\omega t}
\end{aligned}\right\}\quad(8)$$

where C_4 and C_5 are new constants.

Sketches of the field configurations of the $E_{1,1}$-wave and the $E_{2,1}$-wave in the transverse section are shown in figure 2. It is apparent that higher order E-waves may be considered as built up from $E_{1,1}$-waves. We observe that in the $E_{2,1}$-wave a second septum may be placed within the pipe at $\theta=\pi$, providing two independent and separate hollow-pipe channels having the same critical frequency as that of the $E_{2,1}$-wave in the septate coaxial line. This idea has been suggested by Schelkunoff.[5] Figure 3 illustrates the relations between the ratio of the critical wave length to the radius of the outer tube, λ_0/b, and the angular dimension θ_0; evidently the longest critical wave length is afforded by $\theta_0=2\pi$, that is, by the septate coaxial line. The critical wave length increases with increasing b/a, as is also illustrated in figure 3.

$H_{n,m}$-Waves

We place $E_x=0$ and derive the remaining field components from H_x in (1), obtaining:

$$\left.\begin{aligned}
H_x &= \cos\left(\frac{n\pi}{\theta_0}\theta\right)\cdot G\cdot e^{-hx+i\omega t}\\
H_\theta &= \frac{h\frac{n\pi}{\theta_0}}{r\left[h^2+\left(\frac{\omega}{c}\right)^2\right]}\sin\left(\frac{n\pi}{\theta_0}\theta\right)\cdot G\cdot e^{-hx+i\omega t}\\
H_r &= \frac{-h}{h^2+\left(\frac{\omega}{c}\right)^2}\cos\left(\frac{n\pi}{\theta_0}\theta\right)\cdot\frac{dG}{dr}\cdot e^{-hx+i\omega t}\\
E_\theta &= \frac{i\omega\mu}{h^2+\left(\frac{\omega}{c}\right)^2}\cos\left(\frac{n\pi}{\theta_0}\theta\right)\cdot\frac{dG}{dr}\cdot e^{-hx+i\omega t}\\
E_r &= \frac{i\omega\mu\frac{n\pi}{\theta_0}}{r\left[h^2+\left(\frac{\omega}{c}\right)^2\right]}\sin\left(\frac{n\pi}{\theta_0}\theta\right)\cdot G\cdot e^{-hx+i\omega t}
\end{aligned}\right\}\quad(9)$$

where h and G have the same meaning as before. The transcendental equation for h is now

$$\frac{J_k{}'\left(a\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)}{Y_k{}'\left(a\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)}=\frac{J_k{}'\left(b\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)}{Y_k{}'\left(b\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)}\quad(10)$$

The approximate solution of (10) provides the values:

$$\left.\begin{aligned}
\beta &= \sqrt{\left(\frac{\omega}{c}\right)^2-\left[\frac{m}{b-a}+\frac{(4\pi^2n^2+3\theta_0{}^2)(b-a)}{8abm\pi\theta_0{}^2}+\ldots.\right]^2}\\
f_0 &= \frac{c}{2\pi}\left[\frac{m\pi}{b-a}+\frac{(4\pi^2n^2+3\theta_0{}^2)(b-a)}{8abm\pi\theta_0{}^2}+\ldots.\right]
\end{aligned}\right\}\quad(11)$$

A sketch of the field configuration of the $H_{0,1}$-wave is reproduced in figure 2. In this wave, there is only one component of electric intensity, namely in the angular direction, and this component varies

approximately as a half-sinusoid radially. A comparison of (11) with (4) and (5) shows that the critical frequency has the same functional form as that for the *E*-wave.

$H_{1,0}$-Waves

If we let $\theta_0 \to 0$ as $a \to b \to \infty$, the cross section of the pipe approaches a rectangle, and consequently there must be a wave in the septate coaxial cable which will degenerate into the $H_{n,0}$-wave in the rectangular pipe. Thus there is reason to believe that an approximate solution may be obtained for $m=0$ even though (1) is not strictly valid for this value of m. Calculations are possible by graphical methods for the special case $n=1$ and $\theta_0=2\pi$. For this case $k=1/2$, and

$$G=\sqrt{\frac{2}{\pi r\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}}}\left[C_1\sin\left(r\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)-C_2\cos\left(r\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right)\right] \qquad (12)$$

After applying the boundary condition $\frac{dG}{dr}=0$ for $r=a$, b and simplifying we obtain the following transcendental equation for h:

$$\tan\left[(b-a)\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}\right]=\frac{2(b-a)\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}}{1+4ab\left[h^2+\left(\frac{\omega}{c}\right)^2\right]} \qquad (13)$$

This equation has been solved by graphical means for specific ratios of a and b. The constant β and λ_0 can be found in the usual way.

The importance of this wave is that it has the lowest critical frequency of any wave in a septate coaxial line. To illustrate this point, let us consider the case in which $a \to b$. Equation 13 then becomes simply

$$\sqrt{h^2+\left(\frac{\omega}{c}\right)^2}=\frac{1}{2b}$$

i.e.

$$\beta=\sqrt{\left(\frac{\omega}{c}\right)^2-\left(\frac{1}{2b}\right)^2} \qquad (14)$$

and the corresponding critical wave length is:

$$\lambda_0=2\cdot 2\pi b \qquad (15)$$

that is, the critical wave length is twice the circumference of the pipe. The longest critical wave length in a rectangular pipe is twice the width of the pipe, and the longest critical wave length in a circular pipe is 3.41 times the radius. Thus, *the limiting critical wave length of the septate line is greater than that of a circular hollow*

Figure 1. Transverse cross sections of several shapes of hollow pipes; (A) flat rectangular, (B) septate coaxial, (C) spiral, (D) folded. The critical frequencies are approximately the same for each pipe

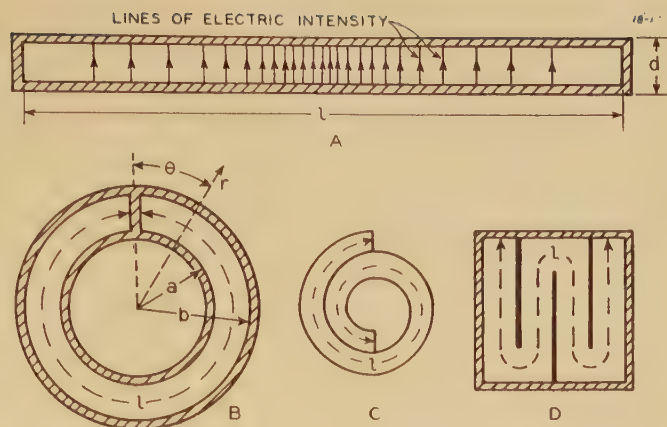


Figure 2. Configuration of the electric field intensity for four types of waves in a septate coaxial cable

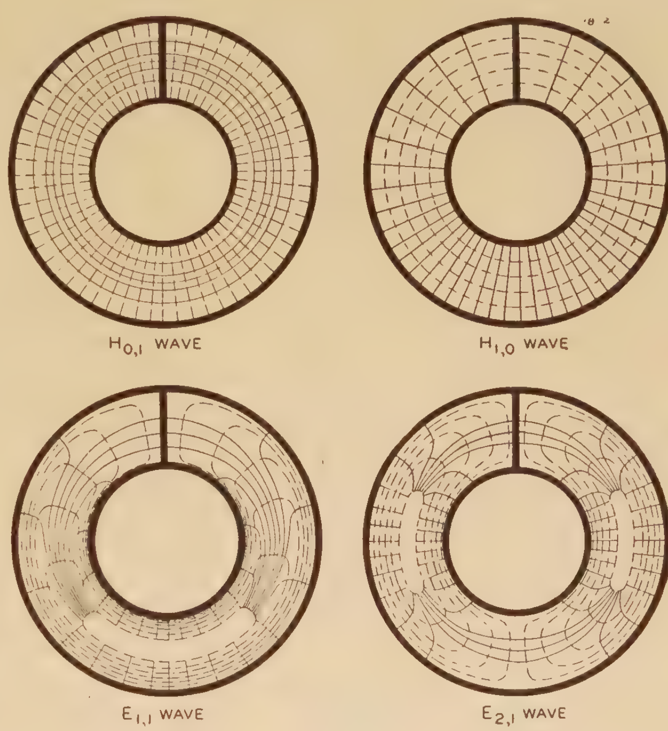
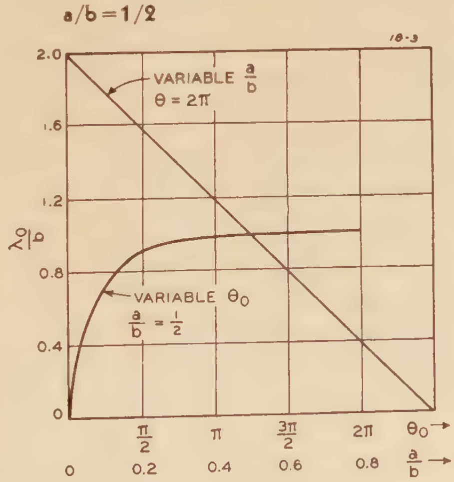


Figure 3 (below). $E_{1,1}$ wave. Relative critical wave length λ_0/b versus a/b in a septate coaxial cable ($\theta_0=2\pi$), and λ_0/b versus θ_0 for $a/b=1/2$



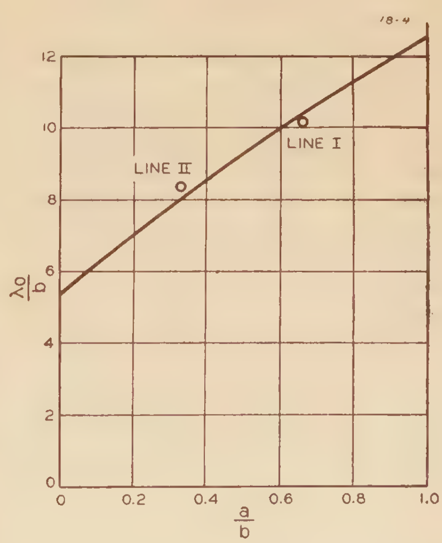


Figure 4. $H_{1,0}$ wave in septate coaxial cable. Relative critical wave length λ_0/b versus a/b. The small circles indicate measured values from two experimental cables

pipe of equal over-all diameter by the ratio $4\pi/3.41=3.68$.

In figure 4 is plotted the ratio of λ_0/b against the ratio of radii a/b for the $H_{1,0}$-wave in septate coaxial line, calculated from (13). The circles are values measured from the two experimental lines discussed later. It may be observed that even for a zero inner radius, the critical wave length is about 1.5 times greater than that for the circular hollow pipe; this latter configuration has been suggested by Sonoda.[6]

The expressions for the field of the $H_{1,0}$-wave may be obtained from (9) by substituting the appropriate values for $h^2+\left(\frac{\omega}{c}\right)^2$. One finds that, in general, there is a small angular component E_θ, as well as the radial component E_r. As b/a approaches unity, however, E_θ vanishes leaving E_r only. This approximate field configuration for $H_{1,0}$-wave is sketched in figure 2 and is given by the following expressions:

$$\left.\begin{aligned} E_r &= C2i\omega\mu b \sin\frac{\theta}{2}\, e^{-hz+i\omega t} \\ H_\theta &= C2hb \sin\frac{\theta}{2}\, e^{-hz+i\omega t} \\ H_z &= C \cos\frac{\theta}{2}\, e^{-hz+i\omega t} \end{aligned}\right\} \quad (16)$$

Experiments and Discussion

Two experimental septate coaxial lines have been investigated that have the following dimensions:

Line I: $a=5.08$ centimeters (2 inches)
$b=7.62$ centimeters (3 inches)

Line II: $a=2.54$ centimeters (1 inch)
$b=7.62$ centimeters (3 inches)

These two lines have the same outer radii but different inner radii.

Experimental measurements have confirmed satisfactorily the essential properties of transmission through the septate coaxial cable. For line I we have measured $\lambda_0=77.5$ centimeters (theoretical value 79.5 centimeters), and for line II 63.5 centimeters (theoretical value 61.3 centimeters). Standing waves along the inside of the line were measured with both ends open, one end open and the other closed, and both ends closed. From such measurements, the wave lengths on the line are plotted as points against the free-space wave lengths in figure 5 for the two experimental lines; the solid curves are theoretical. A satisfactory agreement is found. The field configuration of (16) and figure 2 has been verified by measurements with a small "probe" antenna. The measured field is radial and has a half-sinusoid intensity distribution around the 2π radians from one side of the septum to the other.

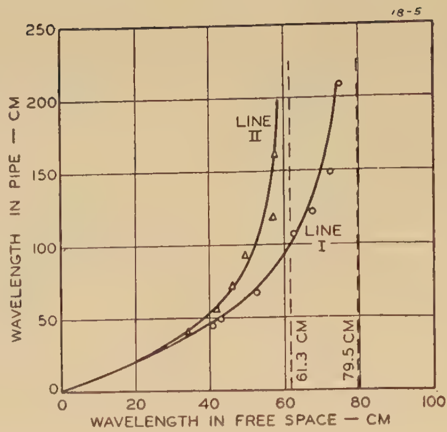


Figure 5. Wave length in two septate coaxial cables versus wave length in free space of the excitation. Solid curves give the theoretical values; dotted lines indicate the theoretical critical wave length, and the circles and triangles represent experimental values

An experimental septate line of the form shown in figure 1*D* was constructed with outside dimensions two by three inches and with three vanes parallel to the three inch sides. The effective length l was about eleven inches, giving an approximate theoretical value for the critical wave length of 55 centimeters. Transmission through this line was effected and a critical wave length of about 50 centimeters was found.

It is known that the cavity contained within a section of hollow pipe closed at both ends manifests pronounced resonance characteristics.[1,2] A highly effective or "high Q" resonator for use in conventional circuits is provided by such a cavity when a connection to the cavity is made by inserting a short length of wire into the cavity through a small hole. Septate lines are readily adapted to this use and offer the advantage of a relatively low resonant frequency for given over-all dimensions. Figure 6 shows a resonator of this kind and a measured response curve obtained in a cavity established in the experimental line II between transverse sheet-metal annuli. Improved construction would improve markedly the sharpness of resonance. The sketch of figure 6 will also serve to show one method of connecting a septate-line terminal to conventional sending or receiving apparatus. Another cavity resonator based on the same principles and providing, too, a relatively long resonant wave length comprises two concentric metal spheroids connected together by a single radial metal rod, which may also serve as a supporting member for the inner spheroid.

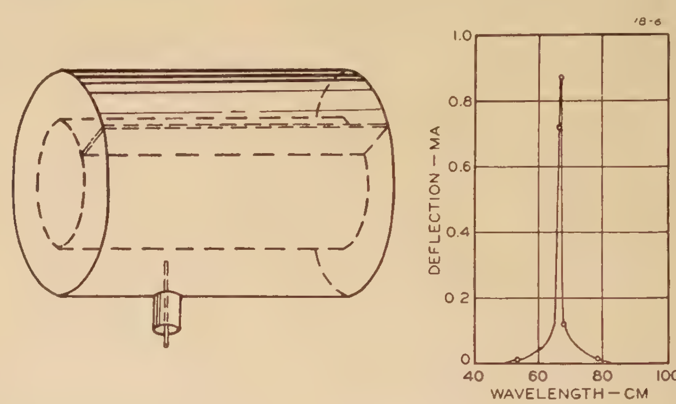


Figure 6. Illustrating a hollow cavity resonator of septate coaxial type and a measured response curve of such a resonator

Bibliography

1. G. C. Southworth, *Bell System Technical Journal*, volume 15, April 1936, pages 284–309.

2. W. L. Barrow, IRE *Proceedings*, volume 24, 1936, pages 1298–1328.

3. L. J. Chu and W. L. Barrow, IRE *Proceedings*, volume 26, 1938, pages 1520–55.

4. On the Roots of the Bessel and Certain Related Functions, J. McMahon. *Annals of Math.*, volume 9, 1894–95, page 23.

5. S. A. Schelkunoff, Brit. Pat. 464,185; and IRE *Proceedings*, volume 25, November (1937), pages 1457–92. U. S. Pat. 2,199,083.

6. S. Sonoda, *Electrotechnical Journal* (Japan), volume 1, number 7, pages 214–15.

Impulse and 60-Cycle Characteristics of Driven Grounds

P. L. BELLASCHI
FELLOW AIEE

I. Introduction

DRIVEN grounds are important in electric power transmission and distribution. In fact, they comprise one of the essential elements in the art of lightning protection. Yet, to this day, the value of protection derived from grounds under actual operating conditions of lightning discharge is difficult to state in full quantitative measure. And the reason for this situation lies partly in the lack of fundamental knowledge of the impulse characteristics of driven grounds. In part, the difficulty also is due to the complex factors that inherently make up driven grounds and ground systems.

A comprehensive survey of principles and methods on driven grounds was issued in 1918 by the Bureau of Standards.[1] Further contributions have appeared since, some presenting new developments and findings,[2] others dealing on theoretical aspects of the problem,[3] and a third group bearing on related questions.[4] In recent years, progress has been centered on the immediate field of application. Here the emphasis has been to obtain effective service with such methods of grounding as lend themselves particularly to economical installation. For instance, a common practice with some utilities nowadays is to drive rods to considerable depths, even down to bedrock, so as to attain the lowest measurable resistance. A recognized practice for securing low-resistance grounds is also to place a sufficient number of electrodes in parallel (multiple grounds). Still another expedient is that of reducing the resistivity of the soil immediately surrounding the electrode by suitable treatment with common salt (NaCl) or other conducting solution. All these developments have been based largely either on 60-cycle values or on closely similar methods of testing. And from the measured 60-cycle values plus what experience would ensue there have been established present practices.

It is a fact that the 60-cycle methods of measurement have the great merit of simplicity[5,6] and it is conceded that experience can often rationalize methods of evaluating performance that are not altogether fundamental. Yet the need of establishing the performance of grounds under the actual service conditions of lightning discharge has long been recognized. In this connection, the tests by H. W. Towne[7] in 1928 and more recently an investigation by H. Norinder[8] has contributed to point out the significance of the impulse characteristics of driven grounds—even though both investigations are somewhat limited in scope considering the extent and practical importance of the subject.

Those versed in the art know that the impulse resistance of a driven ground is below the corresponding megger or 60-cycle measured values. The practice usually followed, to consider the megger values as a basis for design, is also a recognition of this fact. There are other factors which affect design and economy of installation, but these need not be gone into at this time. An immediate fundamental need is for impulse data on actual driven grounds, under impulse currents well approaching lightning conditions. The results of the investigation presented in this paper should therefore be timely and helpful to the art of lightning protection.

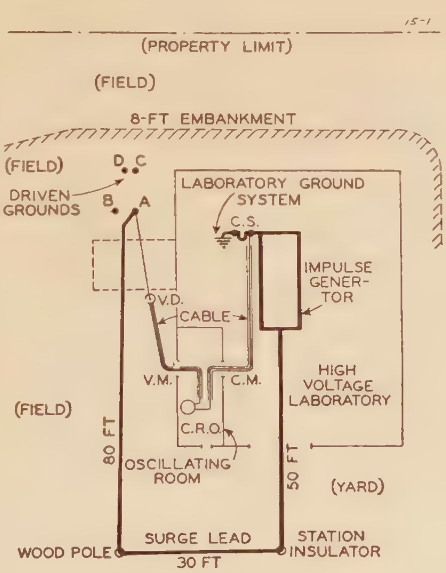


Figure 1. Test arrangement

CRO—Cathode-ray oscillograph
VM—Voltage measurement
VD—Voltage divider
CM—Current measurement
CS—Current shunt

II. Test Arrangement

The Sharon High-Voltage Laboratory is located in the open. This is a favorable circumstance that has facilitated the investigation, for the grounds can be driven in the natural soil within easy reach of a well-equipped impulse laboratory. The arrangement that was used is shown in figure 1.

The impulse generator and the instruments are grounded to the common, low-resistance grid of the laboratory, which measured with the megger 0.9 ohm to earth. The voltages of the driven grounds were recorded at the cathode-ray oscillograph through a voltage divider. Likewise the impulse currents discharged through the driven grounds were measured at the oscillograph, by means of a suitable shunt inserted in the grounded end of the impulse generator. The technique of testing and measurement complies essentially with the recognized methods described in AIEE Standards No. 4 (1940) and in the literature. Other details on the test arrangement will be apparent from figure 1 and the following.

III. Physical Characteristics of Driven Grounds

Four one-inch diameter steel rods, designated as *A*, *B*, *C*, and *D* in figures 1 and 2, were driven in the natural soil outside the laboratory in 1933. They have been in the soil ever since. Two of the rods were driven nine feet in the earth, the other two struck rocks at seven and one-half feet and could not be driven deeper. Early in 1940, after this investigation, two of the rods were removed for inspection. There was no evidence of rusting of the metal at the surface in contact with the soil.

The soil of the grounds is a combination of shale and clay with a mixture of gravel and sand. The earth is normally moist in this location. The physical nature of the soil became more apparent from the examination of a six-foot diameter ten-foot deep hole that was dug in May 1940 near the laboratory at about 25 feet from the location of the grounds. First, sev-

Paper 41-5, recommended by the AIEE committee on power transmission and distribution and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted September 9, 1940; made available for preprinting October 25, 1940.

P. L. Bellaschi is section engineer, transformer engineering department, Westinghouse Electric and Manufacturing Company, Sharon, Pa.

1. For all numbered references, see list at end of paper.

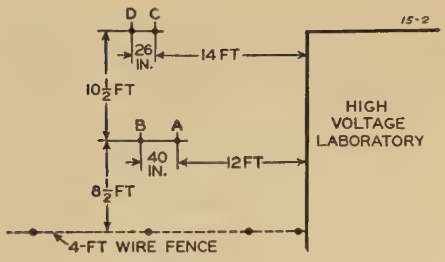


Figure 2. Physical characteristics of driven grounds: A, B, C, and D

Length of rods—ten feet
Diameter of rods—one inch
Taper of end in ground—four inches
Metal (rods)—steel
Depth in ground, *A* and *B*—108 inches
Depth in ground, *C* and *D**—90 inches
Rods driven in 1933

Class of soil—shale and clay with mixture of gravel and sand. Earth naturally moist. Rods in natural soil. Coke cinder on ground surface along fence, extending to rod *A*. Natural surface of soil elsewhere

*C and D struck rocks

eral inches of vegetation soil was removed. Then a combination of clay, sand, and gravel followed to a depth of five feet. In fact a strata of about a foot consisted of a compact layer of gravel and rocks. From five feet down to ten feet, the bottom of the hole, the soil consisted of a thick blue clay. In digging the hole, water started seeping in at a depth of three feet. A rod consisting of multiple sections was driven straight down in the field nearby. It struck solid bedrock at 30 feet. Still other details of the terrain and adjacent objects will be apparent from figures 1 and 2. In short, the class and the nature of the soil are quite typical of conditions that are encountered in Western Pennsylvania and also in other sections of the country.

IV. Tests

(*A*). First series. These tests were completed in November 1939 before the ground had frozen at all. The winter in 1939–1940 got under way late in Western Pennsylvania. Sixty-cycle values for the four driven grounds and for combinations of them are summed up in table I. The voltmeter-ammeter method with sinusoidal waves was applied in these and later tests. Currents ranged from one to five amperes and in one case up to ten amperes. Within these limits the resistance is found to decrease two to three per cent with increase in the current.

The results of the impulse tests which were made at this same time are summarized in table II. The footnote describes the arrangement of the generator. A 6x13 microsecond wave and currents (crest) from 2,000 to 8,000 amperes were applied in these tests. Figure 3-*AF* is a typical oscillogram. The seventh column of table II is of particular interest as it gives the ratio of the impulse to the 60-cycle resistance for the impulse currents discharged through the grounds. The tabulation reveals other points of practical interest. For instance, the presence of a metal fence and a fill-in of coke and cinder adjacent to rods *A* and *B* (figure 2) affected the impulse characteristics of these grounds, particularly at the higher currents. This illustrates the various considerations that require attention when establishing grounds.

(*B*). Second series. The second series of tests was made in January 1940. By this time the ground had frozen at the surface six or eight inches and the temperature had dropped. The resistance had accordingly increased about ten per cent. Through the assistance of the local utility (Pennsylvania Power Company), megger readings of the grounds were taken. These with the 60-cycle values are reported in table III.

Table I. Sixty-Cycle Measurements of Grounds

(Data of Tests 11/27/39)

Driven Grounds	Ammeter (Amps)	Voltmeter* (Volts)	Resistance (Ohms)
A alone	1.01	43.4	43.0
	2.00	86.0	43.0
	2.98	127.2	42.7
	4.00	170.0	42.5
	4.59	193.0	42.1
		Avg. =	42.66
B alone	4.75	189.5	39.9
	4.00	160.5	40.1
	3.01	120.5	40.0
	2.03	81.2	40.0
	1.02	41.5	40.7
		Avg. =	40.1
C alone	4.98	178.5	35.8
	4.30	190.5	35.9
	4.00	142.2	35.5
	3.01	107.0	35.6
	2.13	76.7	36.0
	1.03	37.6	36.4
		Avg. =	35.87
D alone	1.01	37.5	37.2
	2.12	77.3	36.5
	3.01	107.8	35.8
	4.02	143.3	35.7
	5.0	178.0	35.6
	5.35	190.2	35.9
		Avg. =	36.12
A and B in parallel	2.54	66.6	25.9
	3.04	77.1	25.4
	3.98	102.3	25.7
	5.00	129.2	25.9
	6.00	154.0	25.6
	7.00	178.5	25.5
		Avg. =	25.66
C and D in parallel	5.32	190.2	36.1
	4.96	176.0	35.4
	4.03	142.5	35.4
	3.04	107.3	35.3
	2.14	76.7	35.8
	1.03	37.0	35.9
		Avg. =	35.65
A, B, C, and D in parallel	1.28	21.7	16.95
	2.01	33.0	16.45
	2.99	49.5	16.53
	3.97	65.0	16.40
	5.0	82.0	16.40
	6.1	100.0	16.40
	7.1	115.8	16.30
	8.6	139.8	16.30
	10.0	163.5	16.35
		Avg. =	16.45

* Corresponding readings of rms and avg voltmeters all agree within 1.5 per cent.

The impulse data are summarized in table IV. In these tests, the generator was set for a 12x50 microsecond wave and currents (crest) from 700 to 6,500 amperes were available. Typical oscillograms of the current and the voltage are shown in *AX* and *BJ* of figure 3. In the next to the last column of table IV is reported the ratio of the impulse to the 60-cycle resistance for these tests. Again when the two grounds adjacent to the fence, particularly rod *A*, were tested at the higher currents, surface flashover and apparent breakdown in the earth took place. The oscillograms of *BT* (figure 3) illustrate this effect.

(*C*). Other tests. Sixty-cycle check tests on the grounds were made in the summer (1940). They are reported in table III. The data in this table thus show the seasonal variation of the ground resistances.

V. Impulse and 60-Cycle Characteristics

As shown in figure 4, a definite relation holds between the ratio of the impulse to the 60-cycle resistance and the impulse current. The values plotted are for the tests on grounds *C*, *D*, *B*, and the combination *C* and *D* (tables II and IV). The test data are for 6x13 microsecond and 12x50 microsecond waves, but it appears reasonable that the curve applies for impulses over a wider range of waves as encountered in the field. It should be noted that successive applications or tests repeated at different times did not affect the ratio, other than an amount due to inherent variations.

In rounded figures the ratio for these grounds at 1,000, 2,500, 5,000 and 10,000 amperes decreases respectively to the values 0.85, 0.75, 0.65, and 0.55. At higher currents, as 20,000 amperes—provided the potentials developed can be sustained by the grounds, from extrapolation of the curve the ratio does not seem to come materially below 0.50. A lightning stroke to a distribution or a transmission circuit or to a lightning-rod system in general is likely to discharge to earth through more than one path to ground. Therefore the range of currents in figure 4 covers field conditions from a

traveling surge to a direct stroke of lightning.

Two factors in particular governed the low impulse breakdown from rod A to the adjacent wire fence. Rod A was driven eight and one-half feet from the fence, but what seems to have been even a greater influencing factor was the presence of a fill-in of coke and cinders on the ground layer from the fence to the rod. The relative proximity to rod A affected rod B somewhat, but only at the higher currents. Rods C and D on the other hand were amply removed from adjacent bodies and were well surrounded by homogeneous and natural soil, with the result that they sustained the impulse voltages up to the top limit of the test. The performance of rod A illustrates emphatically that other considerations govern the installation of grounds besides those dictated by 60-cycle measurements alone.

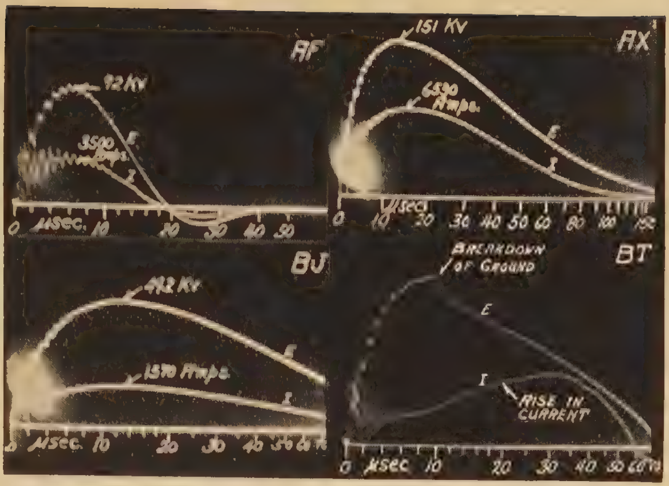


Figure 3. Typical oscillograms of impulse voltages (E) and currents (I)

The 60-cycle resistance for the various parallel combinations of the four rods (table III) is approximately the amount expected from calculation[3] or from previous studies.[1] For example, A and B in parallel calculates 29 ohms, B and D 24.5 ohms and A, B, C, and D 18.5 ohms. Rods C and D in parallel show no reduction due in part to the close proximity of the electrodes and possibly to other factors residing in the earth. However, grounds C and D were good grounds to test with as these were in natural and homogeneous earth, uninfluenced by extraneous bodies and least affected by seasonal variations such as result from changes of the temperature and moisture content in the earth (table III).

For parallel grounds liberally spaced and of normal characteristics, the ratio of impulse to 60-cycle resistance for the individual grounds should hold adequately close for the parallel combination when applied on the basis of the current per rod. The only data available to corroborate this point are the impulse tests on B and D in parallel (table IV).

A characteristic fundamentally significant is the variation of the resistance of grounds during the impulse discharge. For instance, from the voltage and current oscillograms of BJ in figure 3, the resistance from ten to fifty microseconds is found to average 31.5 ohms within about one per cent. Other typical oscillograms are analyzed in table V. The grounds of this investigation exhibited markedly constant resistance, usually within a ten per cent variation, over the part of the discharge that can be considered of more practical significance, i.e., for currents above 50 per cent crest. The relatively constant value of the impulse resistance is apparent also from figure 4 which shows that for a given

Table II. Impulse Measurements of Grounds*

(Date of Tests 11/28/39)

Driven Grounds	Cathode Ray Oscillogram	Wave Form**	Measured Ground Crest Values: Kv	Measured Ground Crest Values: Amps	Impulse Resistance (Ohms)	Ratio of Impulse to 60-Cycle Resistance	Comments
C alone...	AD	Current wave 6x13 MS	166	7,680	21.6	0.60	Refer table I for avg. 60-cycle resistance values. For typical oscillogram, see AF in figure 3
	AE		131	5,500	23.9	0.66	
	AF	Voltage wave 6x13 MS	92	3,500	26.0	0.73	
	AG		56	2,050	27.5	0.77	
D alone...	W-X	Ditto	59	2,240	26.5	0.73	Ditto
	Y		93	3,330	27.9	0.78	
	Z-AA		95	3,330	28.5	0.79	
	AB		132	6,020	21.9	0.61	
	AC		166	7,680	21.6	0.60	
C and D in parallel..	AH	Ditto	58	2,100	27.6	0.77	Ditto
	AI		92	3,520	26.2	0.73	
	AJ-AK		133	4,800	27.6	0.77	
	AL		166	7,050	23.8	0.67	
B alone...	AM	Ditto	159	7,050	22.6	0.56	Collapse of voltage near crest on oscillograms AM and AN due to breakdown in the ground. Current in AM built up to 8,070 amps
	AN		119	4,870	24.4	0.61	
	AO		100	3,200	31.3	0.78	
	AP		61	2,100	29.2	0.73	
A alone...	F-G	Oscillatory wave, 35 MS period	52	11,400	....	....	Low impulse resistance caused by breakdown in ground to wire fence. Adjacent ground and wire fence a factor
	M-N		51	8,060	....	....	
	K-L		43	4,670	....	....	
	I-J		33	2,750	....	....	
A, B, C, and D in parallel	B-C	Oscillatory wave, 35 MS period	53	11,300	....	....	Impulse resistance much similar to values of A alone. Adjacent ground and wire fence a factor
	Q-R		46	8,330	....	....	
	S-T		39	4,920	....	....	
	U-V		31	3,070	....	....	

* Impulse-generator arrangement consisted of ten, 100 kv, 1.5, microfarad capacitor banks in series. Effective series capacitance and inductance of test circuit were respectively 0.15, microfarad and 210, microhenrys. No series resistance inserted in generator (figure 1).

** Positive polarity.

Table III. Sixty-Cycle and Megger Measurements of Grounds

Driven Grounds	Average 60-Cycle Resistance* (Ohms)	Average Megger Resistance** (Ohms)	Average 60-Cycle Resistance*** (Ohms)
A(alone)	46.8	49	33.2
B(alone)	44.1	45	31.3
C(alone)	39.1	39.5	35.7
D(alone)	38.8	38.5	32.0
A and B (in parallel)	28.0	28	
C and D (in parallel)	39.0	39	
B and D (in parallel)	22.4		
A, B, C, and D (in parallel)	17.8	18	

* Measurements by voltmeter-ammeter method, as in table I. Date of tests 1/15/40.

** Measurements recorded with G. J. Biddle Megger. Date of tests 1/31/40.

*** Measurements by voltmeter-ammeter method as in table I. Date of tests 7/22/40.

Table IV. Impulse Measurements of Grounds*

(Date of Tests 1/2/40)

Driven Grounds	Cathode Ray Oscillogram	Wave Form***	Impulse Values: Measured Ground Crest Values, Kv	Impulse Values: Measured Ground Crest Values, Amps	Impulse Values: Impulse Resistance (Ohms)	Impulse Values: Ratio of Impulse to 60-Cycle Resistance	Comments
D alone....	AQ	Current wave 13x48 MS Voltage wave 12x50 MS	24.0	735	32.6	0.85	Refer table II for avg. 60-cycle and Megger resistance values.** For typical oscillogram, see AX in figure 3
	AR		47.7	1,505	31.7	0.82	
	AS		70	2,300	30.4	0.79	
	AT		91	3,140	29.0	0.75	
	AU		110	4,160	26.4	0.69	
	AV		132	5,310	24.9	0.65	
	AW		153	6,340	24.2	0.63	
	AX		151	6,530	23.1	0.60	
	AY		24.4	672	36.3	0.94	
	BE		23.7	672	35.2	0.91	
	BF		89.6	3,390	26.4	0.69	
	BG		129	5,560	23.2	0.60	
	BK		47.6	1,600	29.9	0.78	
C alone....	BB	Ditto	109	4,420	24.7	0.63	For typical oscillogram see BJ in figure 3
	BC		69.8	2,340	29.8	0.76	
	BD		24.4	640	38.2	0.97	
	BH		125.5	5,250	23.9	0.61	
	BI		89.3	3,240	27.5	0.70	
	BJ		49.2	1,570	31.4	0.80	
C and D in parallel	BL	Ditto	23.7	737	32.1	0.82	Ditto
	BM		47.4	1,600	29.6	0.76	
	BN		68.5	2,240	30.6	0.79	
	BO		89.2	3,330	26.8	0.69	
	BP		112	4,160	26.9	0.69	
	BQ		131	5,500	23.8	0.61	
	BR		150	6,780	22.1	0.57	
B alone....	BS	Current wave 10x60 MS Voltage wave 11x60 MS	....	....	.....		Collapse of voltage on front and crest of oscillograms BS, BT, and BU. See oscillogram BT, figure 3. In these tests the ground around the rod was blown up and sparking on fence noted
	BT		134	5,000	26.8	0.60	
	BU		114	4,100	27.8	0.62	
	BV		93.6	2,880	32.5	0.72	
	BW		71.8	1,950	36.8	0.82	
	BX		49	1,310	37.4	0.83	
	BY		25	660	38.0	0.85	
	BZ		25	660	38.0	0.85	
B and D in parallel	CA	Current and voltage waves 15x44 MS	20.4	1,090	18.8	0.84	Ditto
	CB		41.5	2,270	18.3	0.82	
	CC		60.5	3,200	18.9	0.84	
	CD		78.0	4,480	17.4	0.78	

* In these tests the impulse generator arrangement consisted of three, 100 kv, 5 microfarad capacitor banks in series capacitance and inductance of test circuit were respectively 1.667 microfarad and 210 microhenrys. No series resistance inserted in generator (figure 1).

** Avg megger readings (table III) used to calculate ratio in column 7 above.

*** Positive polarity.

current (crest) of the characteristic the ratio does not increase more than 15 per cent at a current (crest) half that value. It is of interest to note that the crest voltage developed precedes the crest current one or two microseconds. As the current recedes on the tail of the wave, the resistance increases (table V). A similar analysis at the lower currents on the front was not possible on account of the superimposed oscillations present in this part of the oscillograms.

The process of the variation of resistance with the current discharge becomes more apparent from the ratio of the impulse to the 60-cycle resistance during the discharge, when referred to the characteristic of figure 4. The ratios of typical oscillograms (table V) are plotted in figure 5 along with the characteristic. Consider oscillograms *AW* and *BR*. As indicated by the arrows in figure 5, as the current rises on the front and approaches crest, the ratio follows the characteristic in a downward trend. When the current reaches crest and then recedes on the tail, the ratio retraces back under the curve traced for the rising part of the current. With further drop of the current the ratio continues to rise, following the characteristic upward. As the case of oscillogram *AS* shows, impulse currents of lower amplitude likewise trace paths that follow near along the characteristic.

While the nature of the oscillograms does not permit complete analysis from the beginning of the front (first few microseconds), yet it is clear from the foregoing that the mechanism of the impulse current discharge for the grounds tested is as follows. The ratio of the impulse to the 60-cycle resistance as the current rises on the front follows in good measure the characteristic (figure 4), down to the value corresponding to the crest current which lies on the characteristic. As the current recedes on the tail the ratio traces a loop under the characteristic for an impulse of high current. Apparently ionized paths or similar effects established by the discharge account for the relatively constant resistance at currents of the discharge above fifty per cent of the crest. As the current drops further, the ratio swings upward with the characteristic. As the lowest current values are reached, a residual voltage may even be present (see *AX* in figure 3).

Though the voltage of driven grounds is usually considered as a resistance drop, some inductance drop is present also. In most cases, however, the inductance of the ground proper is practically unimportant, unless the current rises or recedes unusually abruptly or in the case rods are driven to considerable depth. For each of the driven rods employed in this investigation, the inductance is approximately three microhenrys and even then only a part is effective since the current diminishes along the rod. The time constant (L/R) of the grounds is then less than 0.1 microsecond. Thus for a current rising exponentially to crest in five microseconds, the ohmic drop (Ri) at 2.5

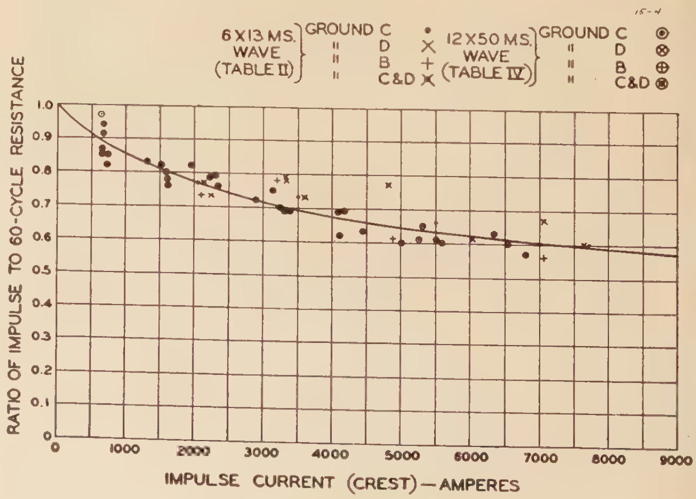


Figure 4. Characteristic of driven grounds: ratio of impulse to 60-cycle resistance versus impulse current (crest)

microseconds is 97 per cent of the impedance drop ($Ri+Ldi/dt$) and as the wave progresses beyond the two merge together since the inductive drop practically disappears. On the other hand it should be amply clear that the inductive effect of leads or in the tower structure that connect the ground proper to the point of incidence of the lightning stroke may be a factor of primary importance in lightning protection.

VII. Discussion of Results

The characteristic of figure 4 applies for a soil of medium resistivity, that is a soil consisting largely of clay with some gravel, etc. The same rods driven in other soils would likely be governed by curves of the same general character, but of different slope. Towne in his investigation[7] on 0.84-inch diameter pipes driven into loose, gravelly soil (artificial fill) obtained ratios from 0.80 to 0.34 for currents (30 x 120 microsecond wave) well under 1,000 amperes. A single ten-foot driven-pipe ground which measured 82 ohms on 60-cycle had a resistance of 50 ohms at 660 amperes—that is a ratio of 0.61. McEachron, Hemstreet, and Rudge in their field tests[9] reported for a pipe driven into the ground, which measured 180 ohms with the megger, a ratio of 0.67 at 550 amperes—the highest impulse current applied. For a 1.3 inch pipe driven four feet into natural soil consisting largely of clay, Norinder found a ratio of 0.76 corresponding to a current of approximately 1,000 amperes. It is of interest to note that in his other tests[8] where the impulse resistance was determined for both positive and negative polarities, the difference found practically was small. In this investigation (tables II and IV) positive impulse currents were applied. In short, it is clear that characteristic curves similar to figure 4 for other typical soils such as sand, etc., obviously are desirable.

Future investigations on high and low resistivity soils may furthermore shed light also on the physical processes that determine the decrease in resistance with increase in current. The present explanation, borne out by this and the investigations cited, is that "the decrease in resistance is probably due to high-resistance contacts between the more conducting particles of soil, at or near the surface of the electrode, which are bridged over by arcs or sparks when sufficient voltage is applied." For instance, the resistivity of the soil at the low 60-cycle currents for grounds *C* and *D* (table III) in the order of 7,500 ohms per cubic centimeter. On the basis of this resistivity the voltage gradient at the rod, when discharging an impulse current of 10,000 amperes (crest), would be $10{,}000 \times 7{,}500/\pi \times 90 \times 6.45$, i.e., 41 kilovolts per centimeter. It is doubtful whether grounds could sustain gradients of this magnitude at all without breakdown. As a matter of fact, from figure 4, the average resistivity of the soil at 10,000 amperes is 0.55 the 60-cycle value to which there corresponds a gradient of 22.5 kilovolts per centimeter. Actually the effective resistivity of the soil at the rod is even less, and the voltage gradient at the rod is correspondingly lower. Studies of the gradients developed should contribute to a better understanding of driven grounds.

Another factor which determines the characteristic of grounds is the size, form, and arrangement of the electrode. Besides rods and pipes, other common types

Table V. Resistance (R) of Grounds at Various Times (T) of Impulse Discharge

T (MS)	E (Kv)	I (Amps)	R (Ohms)	T (MS)	E (Kv)	I (Amps)	R (Ohms)
Driven Ground D (alone)							
Oscillograms AS				**Oscillograms AW**			
4	46.8	1600	29.3	4	108.8	4160	26.1
6	58.5	1090	29.4	6	133	5115	26.0
8	65.8	2180	30.2	8	143.8	5640	25.5
10	69.5	2270	30.6	10	150.5	6080	24.8
12	70.5	2300	30.7	12	153.8	6200	24.8
16	70	2280	30.7	16	152.1	6270	24.3
20	66.9	2160	31.0	20	146.2	6140	23.8
30	56.8	1820	31.2	30	123	5310	23.2
40	46.8	1470	31.8	40	97.8	4030	24.3
50	38.4	1200	32.0	50	76.0	2880	26.4
60	33 4	1025	32.6	60	63.5	2240	28.4
				Oscillograms AX			
				20	145	6400	22.6
				40	96.1	4160	23.1
				60	58.5	2120	27.8
				80	36	960	37.4
				100	24	545	44.0
Driven Ground C (alone)				**Driven Grounds B and D (in parallel)**			
Oscillograms BB				**Oscillograms CD**			
4	76	3010	25.2	4	46.6	2820	16.5
6	93.3	3585	26.0	8	68.8	4040	17.0
8	102.6	4100	25.0	10	74.5	4350	17.1
10	108.3	4225	25.6	12	77.8	4510	17.2
12	109	4415	24.7	16	79.0	4580	17.3
16	107	4415	24.4	20	75.5	4480	16.9
20	102.2	4255	24.0	30	62.1	3520	17.7
30	86.1	3715	23.2	40	45.3	2560	17.9
40	67	2880	23.2	50	32.0	1600	20.0
50	52.9	2240	23.6	60	24.4	1153	21.2
60	43.5	1665	26.2				
Driven Grounds C and D (in parallel)							
Oscillograms BR				**Oscillograms BN**			
4	107	4410	24.3	4	46.8	1538	30.4
8	142.5	6010	23.7	8	64.5	2080	31.0
10	148.5	6400	23.2	10	68.5	2210	31.0
12	150	6720	22.4	12	68.8	2240	30.7
16	147.8	6790	21.8	16	67.1	2210	30.4
20	141.8	6720	21.1	20	63.8	2115	30.2
30	117	5760	20.3	30	54.8	1890	29.0
40	90.1	4350	20.7	40	44.8	1508	29.5
50	68.1	3200	21.3	50	35.8	1150	31.0
60	55.4	2430	22.8	60	30.8	960	32.0
70	43.4	1760	24.7	70	26.1	800	32.6

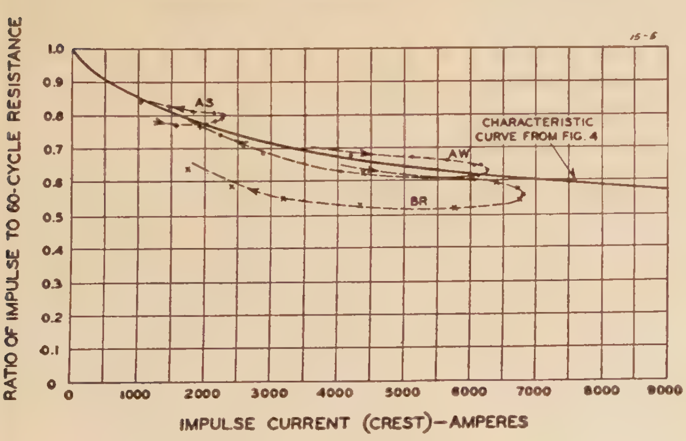


Figure 5. Variation of "impulse resistance to 60-cycle resistance" ratio during impulse current discharge compared with characteristic (figure 4)

Minimum Insulation Level for Lightning Protection of Medium-Voltage Lines

H. N. EKVALL
ASSOCIATE AIEE

LIGHTNING protection of wood pole lines is a problem of wide interest among operating companies. It is therefore timely to cite the experience of the Philadelphia Electric Company during the six year period, 1935–40, in successfully renovizing its 13 and 33 kv wood pole lines to reduce trouble.

In 1935 this company was faced with the problem of determining how to materially reduce lightning trouble on a variety of pole top configurations at a minimum of expense. It had been shown by Andrews and Stroup[1] that wood insulation could be employed effectively. However, no information was available to indicate what reduction in trouble could be obtained for various increases in insulation. The high ridge pin configuration proposed by these authors, while reported to be very effective, could not be applied to many of the existing line structures without making major changes in construction at considerable expense. There was therefore need for an investigation into the degree of protection afforded by lesser amounts of insulation. With this problem in mind, the author set out to make a detailed investigation of the performance of the various types of structures and to correlate their insulation strength with their rate of trouble.

It was discovered from these correlations that substantial reductions in trouble occurred with increases in insulation strength up to a certain level and that equal increases above this level were much less effective. It was evident, therefore, that the greatest reduction in trouble, at least cost, could be obtained by improving those structures which were below the indicated level. As the result of these findings, minimum insulation levels were adopted for both the 13 and 33 kv systems and used as a basis for renovizing the lines. The levels adopted were somewhat below the insulation strength of the high ridge pin construction proposed by Andrews and Stroup.

Besides establishing a minimum insulation level on which to base construction practice, the data obtained were also found very helpful in predicting what reduction in trouble might be obtained from construction changes and thereby aided in justifying the expenditure required.

This paper describes the procedure followed in determining the susceptibility to lightning trouble of pole line structures of various insulation strengths, indicates what changes were made to structures below the required minimum level and shows what reduction in trouble was obtained by these changes on the 13 and 33 kv systems.

Paper 41-14, recommended by the AIEE committee on power transmission and distribution and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted July 29, 1940; made available for preprinting November 28, 1940.

H. N. EKVALL is engineer for the Philadelphia Electric Company, Philadelphia, Pa.

1. For all numbered references, see list at end of paper.

Description of Systems

The 13 kv lines investigated were those in Philadelphia. They are three wire three-phase circuits with the neutral g ounded through a four ohm resistor at the generating stations and through a grounding transformer at one substation. Although operated as radial circuits, they form a network over the city with numerous breakdowns to each other through pole top air break switches. These lines have a total length of 125 circuit miles, and an average length per circuit of 2.6 miles.

The 33 kv lines are in the suburban territory covering an area of approximately 1,400 square miles surrounding Philadelphia. They are three wire three-phase circuits, with the neutral solidly

---

of grounds which serve to conduct lightning currents into the earth, are the footing of transmission-line towers and of other structures such as are found at substations, etc. In general, it appears from the preceding considerations and the test data that electrodes which contribute inherently to lower the current density in the soil are likely to influence the characteristic in a direction towards a more constant resistance with increase in current. The practical usefulness and basic importance in establishing characteristic curves for typical forms of ground electrodes need not be emphasized. Through such an approach the problems presented from grounds can be rationalized more readily and the value derived from grounds assessed in a more quantitative measure. An effective ground means greater safety in protection and an improved ground may mean reduced insulation or insulation clearances with the resulting benefit of reduced costs.

VII. Summary

This investigation presents test data on the impulse and 60-cycle characteristics of common rods driven in natural soil (largely clay composition). It sums up and analyzes the results in the characteristic curve of the ratio of impulse to 60-cycle resistance for impulse currents that represent conditions ranging from a traveling surge to direct strokes of lightning. The basic reasons for the performance of grounds to impulse currents as they do are pointed out insofar as the experimental data and observations permit to do so. From this investigation the desirability of establishing the characteristic for other typical soils and for other common types of grounds (electrodes) is apparent.

References

1. GROUND CONNECTIONS FOR ELECTRICAL SYSTEMS, O. S. Peters. Technological Paper No. 108 of the Bureau of Standards, June 1918.

2. PRACTICAL ASPECTS OF EARTHING, E. Fawssett, H. W. Grimmit, G. F. Shotter, and H. G. Taylor. *Journal* of the Institution of Electrical Engineers, October, 1940, page 357.

3. CALCULATION OF RESISTANCES TO GROUND, H. B. Dwight. AIEE TRANSACTIONS, volume 55, 1936 (December section), page 1319.

4. EARTH RESISTIVITY AND GEOLOGICAL STRUCTURE, R. H. Gard. AIEE TRANSACTIONS, volume 54, 1935 (November section), page 1153.

5. TESTING LIGHTNING ARRESTER GROUNDS, E. Beck. AIEE Lightning Reference Book, page 381.

6. Various bulletins and trade publications on ground rods and ground testing: Anaconda, James C. Biddle Company, Borden Electric Company, Copperweld.

7. IMPULSE CHARACTERISTICS OF DRIVEN GROUNDS, H. M. Towne. AIEE Lightning Reference Book, page 259.

8. THE IMPULSE RESISTANCE OF EARTHING CONDUCTORS, H. Norinder and R. Nordell. CIGRÉ paper 302, presented at the 1939 Paris meeting.

9. TRAVELING WAVES ON TRANSMISSION LINES WITH ARTIFICIAL LIGHTNING SURGES, K. B. McEachron, J. G. Hemstreet, and W. J. Rudge. AIEE Lightning Reference Book, page 722.

10. COUNTERPOISE TESTS AT TRAFFORD, C. L. Fortescue and F. D. Fielder. AIEE Lightning Reference Book, page 1314.

11. CHARTS SHOW GROUND ROD DEPTH FOR ANY RESISTANCE—IN ADVANCE, R. M. Schahfer and W. H. Knutz. *Electrical World*, October 19, 1940.

grounded at two points centrally located on the system. These lines are primarily connecting links between the suburban 33 kv-4 kv substations and have a total length of 460 circuit miles and an average length per circuit of 14.2 miles.

Basis for Protection

Experience on the lines of the Philadelphia Electric Company had shown that power arcs resulting from lightning flashovers were the principal source of trouble and that lightning itself seldom caused more than slight splintering of the pole or crossarm. It was concluded, therefore, that a good basis for protection would be one which minimized the chances for power arc formation. The method adopted was to lengthen the initial arc-over paths along the pole and crossarm by increasing the insulation between phases and between phase and ground.

In determining the insulation strength of the various types of structures it appeared desirable from the above experience to base it on factors directly influencing power arc formation. Two factors which appeared predominant were the length of insulation in the arc-over path and the 60 cycle voltage across the path. Accordingly, these terms were used as a basis for measurement of insulation strength.

Measurement of Insulation Length

At the beginning of this investigation, field surveys were conducted which showed that both the 13 and 33 kv systems had a large variety of pole top arrangements, resulting in a wide range of insulation lengths along the arc-over paths between phases and between phase and ground. It was therefore necessary to make all comparisons of power arc trouble on the basis of individual structures rather than on miles of line, as is frequently done. Accordingly detailed information was obtained for each pole indicating such things as length of crossarm, type of insulators and braces, location of line wires, guys, ground wires, and other pertinent data. From these data the length of insulation in the arc-over path between phases and between phase and ground was determined for each structure. In all, approximately 20,000 poles were investigated.

In each case the arc-over path was considered as being along the surface of the pole or crossarm rather than directly between wires in air. The length of insulation in the arc-over path was taken as the sum of the porcelain and wood insulation lengths. Parts of the crossarm or pole shunted by metallic hardware were excluded. The insulation length assigned to each pin type insulator was its wet arc-over distance as given by the manufacturer's catalog, while for a string of suspension insulators their insulation length was taken to be the wet arc-over of one unit plus the distance between centers of successive additional units. This was done because this distance is the length of the arc-over path after the lightning has flashed over the string.

The measurement of length of insulation in the arc-over path is illustrated in figures 1 and 2. In figure 1 the total length of insulation from phase A to phase B is 84 inches, and from phase A to ground G is 49 inches. The wet arc-over distance for each 33 kv pin type insulator is six inches. In figure 2 the suspension insulators are ten inches in diameter, have a distance between centers of $5^3/_4$ inches, and a wet arc-over per unit of approximately four inches. Adding the four inch wet arc-over distance to four times $5^3/_4$ inches (the distance between centers of insulators) gives a total arc-over distance of 27 inches for the five-unit string. This added to the 24 inches of wood on the pole gives a phase to ground insulation length of 51 inches.

Unit of Insulation Strength

For simplicity, it was found desirable to combine the two factors, insulation length and 60 cycle voltage, into a common unit of insulation strength called "inches per kv." This unit is simply the length of insulation in the arc-over path divided by the operating voltage. When determining the phase to phase insulation strength the length of insulation between phases is divided by the line to line voltage, whereas for phase to ground strength the length of insulation between phase and ground is divided by the line to ground voltage. Referring to figure 2, the insulation strength between phases A and B is 3.1 inches per kv, or 102 inches divided by the line to line voltage, 33 kv. Between phase A and the guy it is 2.7 inches per kv, or 51 inches divided by line to ground voltage, 19 kv. For this structure the minimum is 2.7 inches per kv. All comparisons in this investigation were based on the minimum insulation strength of each structure expressed in inches per kv, irrespective of whether it was phase to phase or phase to ground. This was done because experience had shown that phase to phase as well as phase to ground strengths are important in the control of power arc formation.

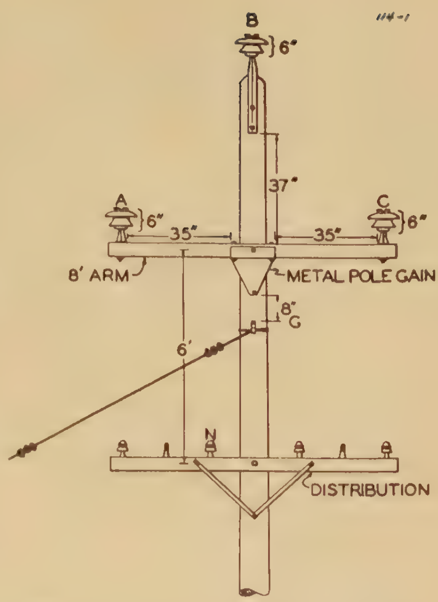


Figure 1. 33 kv high ridge pin structure

	Insulation Length Inches	Insulation Strength Inches Per Kv
A to B	84	2.6
A to C	82	2.5
A to G	49	2.6
B to G	51	2.7

Using "inches per kv" as the basis for measurement has the advantage over using lightning flashover data of employing two readily measurable factors, insulation length and 60 cycle voltage, which directly govern the tendency for formation of power arcs following lightning flashover. Taking these factors into account appears to meet in part the need expressed by Andrews[2] in 1938 for data on factors influencing power-follow in addition to lightning flashover data. Factors such as magnitude of short circuit current, circuit tripping time, wind and rain also have some influence, but inclusion of them was beyond the scope of this investigation. There is still need for more study of the influence of all these factors on power arc formation.

It should also be appreciated that the results given here are based on empirical data and that investigations under controlled laboratory conditions with lightning surges superimposed on the 60 cycle voltages would be of considerable value.

Minimum Insulation Level

Having determined the minimum insulation strength in "inches per kv" for each structure from field surveys, the next step was to classify structures according to their strength. The annual rate of trouble experienced in power arc faults per 100 circuit structures was then determined for each group and a susceptibility curve

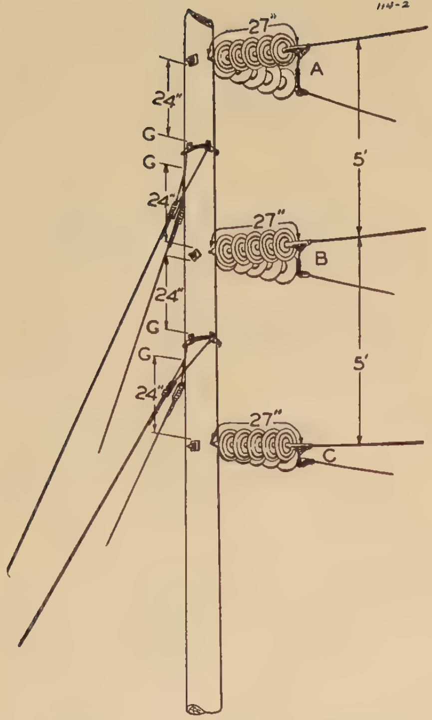


Figure 2. 33 kv corner pole structure

	Insulation Length Inches	Insulation Strength Inches Per Kv
A to *B*	102	3.1
A to *G*	51	2.7

plotted for each system of the two voltage classes studied. Susceptibility curves based on the composite results for the five year period 1935–39 are shown in figure 3. These indicate that as the insulation strength increases up to a certain level, the rate of power arc faults decreases quite rapidly, whereas further increases beyond this level are much less effective. The fact that the 13 and 33 kv curves do not parallel each other is probably due to the dissimilarity of the two systems in regard to location, number of structures in a given insulation strength class, storm exposure, and other variables referred to in the preceding section of this paper. The significant thing is that both curves show the same general trend and permit selection of a minimum insulation level on which to base construction practice.

Based on susceptibility curves developed earlier in this investigation and similar to those in figure 3, a minimum insulation level of two inches per kv was adopted for the 33 kv system and 3.5 inches per kv for the 13 kv system. These points are just below the knee of the curves. Also, much of the improvement work could be carried on fairly economically up to these levels with substantial reductions in trouble. A level above two inches per kv for 33 kv lines would have been difficult to obtain on many existing structures without replacing the present poles with larger ones. Also, a level above 3.5 inches per kv for 13 kv lines would have required increasing the insulation strength on a large number of low ridge pin poles which were already 3.5 inches per kv, and which had been changed from flat top to this configuration prior to this investigation. The principal aim of the improvement program was to raise the insulation strength of structures which were below the adopted minimum to that value or better. Just how much insulation strength is required for immunity to power arc trouble is not known. However, thus far with 2,300 structure years of experience no trouble has occurred on 13 kv high ridge pin configuration in Philadelphia having a minimum insulation strength of from 6.5 to 7 inches per kv. For the 33 kv system there appears to be no practical value of insulation which will entirely prevent power arc trouble.

Besides being of value in adopting a minimum insulation level the susceptibility curves provide a means for predicting what reduction in power arc faults may be expected by increasing insulation strength from one level to another. Such predictions are of value in determining whether proposed changes on the lines may be economically justified. Being based on five years' experience on a large number of circuit structures, the curves in figure 3 are believed to closely approximate the average annual performance that may be expected for various levels of insulation strength.

In the development of the susceptibility curves power arc faults were selected on the following basis. Any evidence of power arc damage to wires or insulators on a given structure of a single circuit line was classed as a single case of power arc trouble, irrespective of the number of phases involved. Similarly evidence of power arc damage to two circuits on the same structure was classed as two cases of trouble. This classification was necessary because both single and twin circuit structures were included in the analysis. For the same reason it was necessary to place the rate of trouble on a "circuit structure" basis rather than just on a "structure" basis. Thus the number of circuit structures on a single circuit line was taken to equal the number of poles in that line, whereas the number of circuit structures in a twin circuit line was double the number of poles.

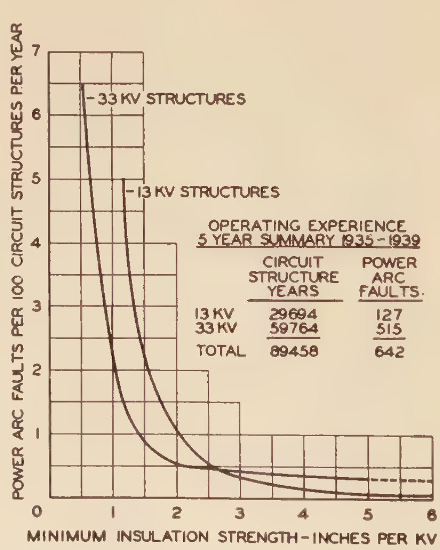


Figure 3. susceptibility of 13 and 33 kv aerial circuit structures to power arc damage following lightning flashover

Line Improvements

By the close of the 1940 lightning season, the 13 kv line improvement work in Philadelphia had been virtually completed, with approximately 95 per cent of the circuit structures having an insulation strength of 3.5 inches per kv or better. Similarly, improvements to the 33 kv lines had brought about 75 per cent of that system up to two inches per kv or better.

The principal changes on the 13 kv lines consisted of (*a*) removal, relocation or insulation of guys, (*b*) replacement of metal with wood braces, (*c*) use of porcelain or wood sections in the horizontal and vertical operating bars of gang operated air break switches, (*d*) rebuilding of deadends and corners, and (*e*) changeover from low ridge pin to high ridge pin configuration by lowering the crossarm or use of wood pole extensions. These changes were made to obtain additional wood insulation between phases and between phase and ground.

As already mentioned, much of the 13 kv construction in Philadelphia had been changed over from flat top to low ridge pin, figure 4, prior to this investigation. However, where pole space permitted lowering the crossarm two to four feet at little cost, this was done to obtain high ridge pin construction. In replacing old poles and in building new lines, the four foot high ridge pin configuration has been used. This construction gives approximately equal insulation strength between phases *A* and *B*, *B* and *C*, and *C* and *A*. It also has about the same dimensions as the 33 kv high ridge pin shown in figure 1 and permits ready conversion to 33 kv operation by merely changing to larger insulators. High ridge pin configuration has been applied to a

number of 13 kv pole top switches in Philadelphia.

Changes on the 33 kv system were similar to those cited above. However, much of the improvement to this system has been obtained through relocation or removal of guys and removal of overhead and vertical ground wires. Whatever benefit may have been obtained from the overhead ground wires was nullified by their iron supports and vertical ground leads shunting out the wood pole insulation and thus permitting a ready path for formation of power arcs. Breakage of the overhead ground wires in storms was also another cause for their removal. Pole gains of the type shown in figure 1 have been used extensively to replace metal braces. Isolated groups of steel towers in the wood pole lines at such places as railroad crossings have been improved by replacing metal arms with wood or by adding suspension insulator units up to a total of seven per string. Pole top switches with steel supporting frames and steel operating rods have been particularly susceptible to trouble. Many of these have been rebuilt, using wood supporting members and wood sections in the operating bar. A new design 33 kv vertical switch using post type insulators mounted on two rotating wood uprights is shown in figure 5. This has four feet separation between phases and an insulation strength of two inches per kv. Also on new lines, construction of the type shown in figures 1 and 2 is being used.

Because guys have been one of the chief sources of lightning trouble on both the 13 and 33 kv systems, it is well to consider some of the remedies and certain conditions that should be looked for when trying to obtain additional wood insulation. In most instances improvement has been

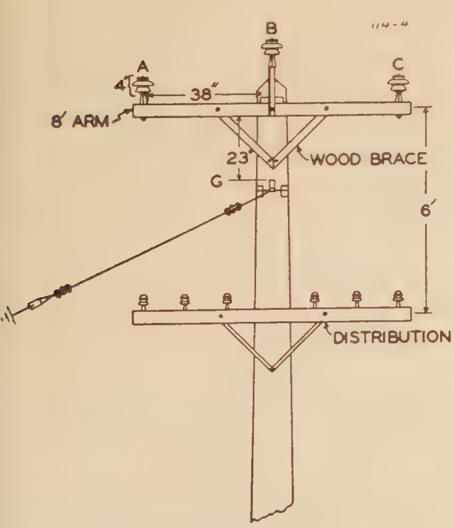


Figure 4. 13 kv low ridge pin structure

Figure 5. 33 kv vertical switch

obtained by lowering or raising guys to the position on the pole which provides the desired amount of wood insulation without sacrificing mechanical strength. Often side guys were found attached to stub poles, which in turn were guyed to ground. Separation of the guys on the stub pole in the manner shown in figure 6 was frequently done to gain wood insulation. This diagram shows an air clearance of nine inches between the guys on the stub so that lightning flashover would be more likely to go across the 15 inches of wood pole rather than across the air gap. If flashover should occur across the air gap, the power arc which followed would therefore be shorter and not so readily interrupted as if flashover had originated across the 15 inches of wood. As a basis for determining desirable air clearance for guys, one inch of air path was taken approximately to equal two inches of wood on an impulse strength basis. Where practical, therefore, an effort was made to have the air gap distance a little greater than half the length of wood insulation.

Guys were sometimes found too close to line wires, or were brought down at such a sharp angle as to shunt out much of the wood pole insulation by passing too close to a through bolt holding the line suspension insulators as in the case of corner poles. Also, guys which were supposedly insulated from ground were found close to or in contact with lightning arrester ground wires, pipes and conduits on the pole, or to other grounded objects. Tail guys used in dead-ending the three phases of a line were found to converge on a common point of attachment. This condition permitted phase to phase short circuits through the guys when flashover of the dead-end insulators occurred and

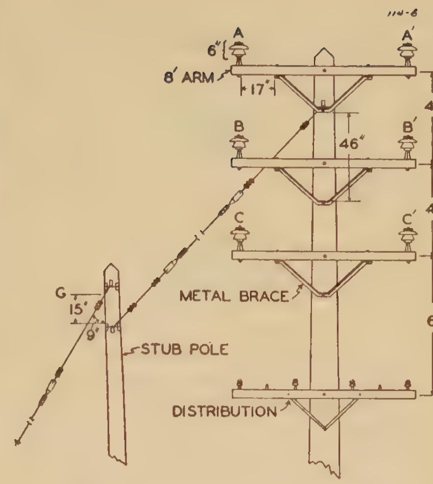


Figure 6. 33 kv twin circuit structure

was remedied by obtaining vertical separation of the three guys on the attachment pole. Where guys could not be effectively relocated, wood guy strain insulators equipped with arcing horns have been used in a number of instances.

In this study the conventional porcelain guy insulators were assumed to provide no insulation strength because of their small wet arc-over distance.

Performance

While the susceptibility curves indicate what reduction in rate of trouble can be obtained on individual structures through increases in insulation strength, it is of interest to note what over-all decrease in line interruptions and power arc faults has been obtained through the various changes that have been made.

On the 13 kv system in Philadelphia line interruptions during lightning storms decreased from 55 per 100 circuit miles in 1935 to 14 in 1940, a reduction of 75 per cent. Similarly, 33 kv line interruptions decreased 62 per cent, or from 45 to 17 per 100 circuit miles from 1937 to 1940, in which period almost all of the improvement work was done. While variations in the severity of the lightning seasons affect such comparisons, it is believed that the reductions in line interruptions given above were largely due to the line improvements.

Approximately the same percentage reduction in power arc faults as in line interruptions were obtained. On the 33 kv lines cases of pole splintering without accompanying power arc trouble showed an appreciable increase during the period of line renovation. This was expected and further confirms the results showing the value of increased insulation in reducing power arc trouble.

There has been no apparent increase in

D-C Breakdown Strength of Air and of Freon in a Uniform Field at High Pressures

J. G. TRUMP
ASSOCIATE AIEE

F. J. SAFFORD
ASSOCIATE AIEE

R. W. CLOUD
ASSOCIATE AIEE

Synopsis: D-c breakdown studies of air in a uniform field have been extended to 1,000 kv. D-c studies of Freon (CCl_2F_2) have been extended to over 350 kv and to 135 pounds per square inch absolute. The departure from Paschen's law at the higher values of pressure times gap is noted. The mechanisms which account for the higher insulating strength of such gaseous compounds as CCl_2F_2 are outlined and their possibilities and limitations in the insulation of high-voltage apparatus are briefly discussed.

Introduction

It has long been recognized[1] that the insulating strength of air and other gases in a uniform field increases with the pressure. The classical analysis of the voltage-breakdown mechanism and its dependence on pressure and other properties of the gas was made by Townsend in 1903.[2] This explanation was based on the ionization of the interelectrode gas by both electron and positive-ion collision—a process which Townsend showed would become cumulative when the positive ions produced by the electrons moving toward the anode under the influence of the field become capable, by their ionizing collisions, of producing an even greater number of new electrons. Since that time, Townsend's second coefficient β has been reinterpreted to include various other mechanisms which contribute regeneratively to the charged particles in the interelectrode space. Among these are photoelectric emission, secondary electron emission due to positive-ion impact at the cathode, photo-ionization in the gas, and ionization by excited atoms and by multiple collisions. In addition, it has become evident that any explanation of high-pressure breakdown must also take into account the several processes of ion removal and the important influence of space charge and the myriads of tiny self-healing electron avalanches in modifying the electric field.[3] Recognition of these various ion-producing, ion-removing, and field-modifying mechanisms has clarified the general picture of breakdown in gases but at the same time has shown it to be too intricate for full quantitative description. Because of this complexity, knowledge of gaseous insulation continues to depend to a large extent on the experimental determination of the breakdown strength and pre-breakdown behavior of the various gases as a function of pressure and electrode geometry, and on the investigation—both under simplified and under practical conditions—of the relative importance of the several mechanisms involved in gaseous breakdown. This paper extends d-c breakdown studies in air and in Freon 12 (dichlorodifluoromethane) at high pressures and in a uniform field to higher voltages than have been reported previously, and indicates reasons for the observed departures from Paschen's law and for the relatively high insulating strength of the Freon.

Apparatus

The investigation of the breakdown of air at voltages up to 1,000 kv was made with a pressure-insulated electrostatic generator[4] developed at the Institute for the production of high-voltage X rays for medical use. The uniform gap was established by a fixed electrode of polished steel* attached to the high-voltage terminal and a similar but movable electrode connected to the tank. The diameter of these electrodes was six inches, and their shape was such that in the central gap area the electric field was a maximum and substantially uniform for gaps up to one and one-half inches. The voltage was measured by a generating voltmeter[5] with an estimated error of less than two per cent.

Most of the studies of the breakdown of Freon were made in a 13-inch-diameter

Paper 41-9, recommended by the AIEE committee on basic sciences and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted September 16, 1940; made available for preprinting November 6, 1940.

J. G. Trump is assistant professor of electrical engineering, F. J. Safford, and R. W. Cloud are research assistants, electrical engineering department, at Massachusetts Institute of Technology, Cambridge, Mass.

1. For all numbered references, see list at end of paper.

* The several grades of steel, stainless steel, brass, and aluminum give about the same results as electrode materials, the breakdown voltage at higher pressure and gradient being dependent primarily on the smoothness and freedom from contamination of the surfaces rather than on the nature of the metal itself.

---

substation lightning trouble on the 13 and 33 kv systems due to the increase in line insulation.

Summary and Conclusions

1. On the 13 and 33 kv wood pole lines of the Philadelphia Electric Company power arcs following lightning flashover were the principal source of trouble, while lightning itself seldom caused more than slight splintering of the pole or crossarm.

2. The chances of a power arc forming after lightning flashover depend upon the 60 cycle voltage and length of insulation. These factors were combined into a common unit of insulation strength called "inches per kv."

3. Increases in insulation strength up to approximately two inches per kv for 33 kv lines and 3.5 inches per kv for 13 kv lines were found to be much more effective in reducing trouble than increases beyond these limits.

4. These limits were adopted by the Philadelphia Electric Company as a practical minimum of insulation strength on which to base construction practice in renovizing its lines.

5. Improvements to obtain the minimum insulation strength of 3.5 inches per kv or better on the 13 kv system in Philadelphia are believed largely responsible for a 75 per cent reduction in line interruptions during lightning storms from 1935 to 1940.

6. Similar improvements to obtain the minimum insulation strength of two inches per kv or better on the 33 kv system are believed largely responsible for a 62 per cent reduction in line interruptions during lightning storms from 1937 to 1940.

7. The amount of insulation required for immunity to power arc trouble is not known. However, thus far no trouble has occurred on 13 kv high ridge pin configuration having a minimum insulation strength of from 6.5 to 7 inches per kv. For 33 kv there appears to be no practical value of insulation which will entirely eliminate power arc trouble.

References

1. Transmission Research and Design With the Field as a Laboratory, F. E. Andrews and C. L. Stroup. AIEE Transactions, volume 49, 1930, pages 959–68.

2. Lightning Strength of Wood in Power Transmission Structures, Philip Sporn, J. T. Lusignan, Jr., discussion by F. E. Andrews. AIEE Transactions, volume 57, 1938 (July section), page 410.

steel pressure tank[6] provided with a Textolite high-voltage bushing for 500 kv. External heaters were applied to the tank so that vapor pressures up to 140 pounds per square inch absolute could be maintained. The high-voltage source was a 500-kv constant-potential electrostatic generator of the Van de Graaff type. The voltage was measured with an error of less than three per cent, using a calibrated spiral-line type of high resistance.

Insulating Strength of Compressed Air in a Uniform Field

Figure 1 gives the d-c breakdown voltage of dry air in a uniform field for a range of pressures from 1 to 13 atmospheres and electrode separations up to one and one-half inches. This figure also gives similar data taken in the same apparatus on the breakdown of Freon at pressures up to 45 pounds per square inch absolute, and for voltages up to 500 kv. These Freon data are discussed later in this report. It is to be observed that at each pressure the voltage increases linearly with electrode separation. Since both the voltage and the product of pressure times gap are substantially higher than any heretofore reported, the data on compressed-air insulation are examined with reference to Paschen's law.

It was stated by Paschen[7] and it followed from Townsend's and subsequent analyses that for a given gas and a uniform field the sparking voltage is a function of the product of the interelectrode gap and the gas pressure. The more general similarity law enunciated 50 years later declares the sparking potential of a gas to remain unchanged if the physical dimensions of the electrodes and gap are changed in the inverse ratio to the change in pressure. Paschen's law has been checked at pressures ranging from the critical pressure (corresponding to minimum sparking potential) to many atmospheres, and experimenters have been generally agreed that Paschen's law holds up to gas pressures of ten atmospheres.[8] Some experimenters have measured the linear increase in the breakdown voltage across a uniform gap with gas pressure, and concluded Paschen's law to hold until departure from the linearity was found. It must be pointed out, however, that Paschen's law does not predict this linearity of voltage and pressure, though this linearity does exist over a considerable pressure range. Paschen's law predicts for a uniform field the constancy of the breakdown potential when the product of the interelectrode gap and the gas pressure is constant. In figure 2 the data in figure 1 are replotted to show the variation with pressure of the d-c breakdown voltage across a uniform field in air for constant values of *pd* from 10 to 240 pounds per inch. (One pound per inch = 131 millimeters Hg$\times$centimeter.) It is seen that the relative voltage change with pressure is greater at the higher values of *pd*. The bulk of the recorded data lies in the realm in which Paschen's law fails, so that a slight reduction of voltage with pressure is shown even for the lowest value of *pd*.

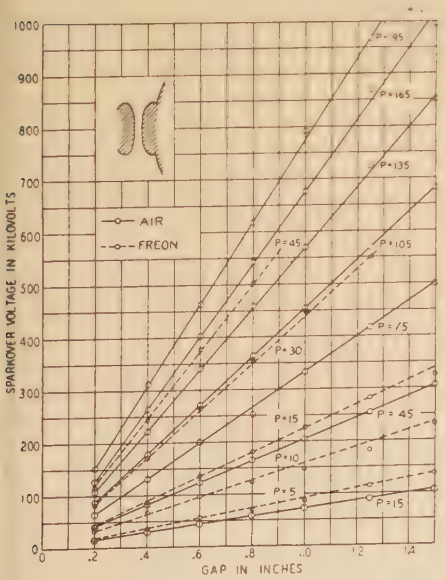


Figure 1. Increase of d-c spark-over voltage of air and of Freon 12 with electrode separation at several absolute pressures in pounds per square inch. Uniform field

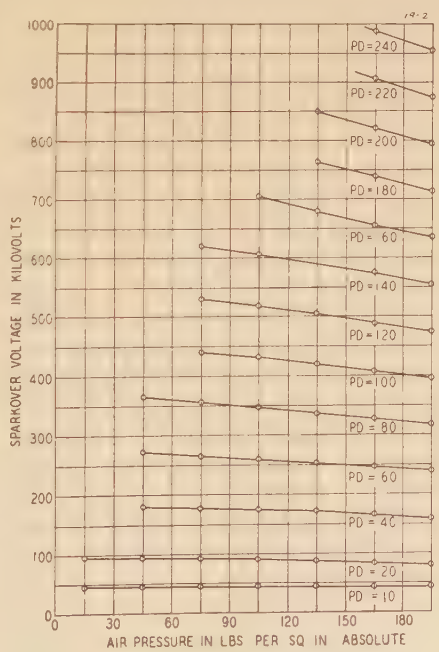


Figure 2. The spark-over voltage in air as a function of pressure for constant values of pressure times gap in pounds per inch

The decrease in the breakdown voltage with increasing pressure at the higher values of *pd* is not unexpected, since the higher gradients favor photoelectric and secondary emission at the cathode. The contribution of the electrode surfaces to the ionization by high field emission may become appreciable at gradients of the order of 10^5 volts per inch, particularly for surfaces that have been inadequately cleaned and conditioned by sparkover or other discharges. Moreover, at higher pressures the reduced mobility and diffusivity of the ions in the interelectrode gap increase the field distortion due to space charge and hence upset the ideal considerations upon which Paschen's law is based. Analysis of other data indicates that departure from Paschen's law begins at values of *pd* of about two pounds per inch. Differences in the experimental values of *pd* at which Paschen's law has been observed to fail are probably due largely to variations in electrode conditioning, which has a marked effect on the breakdown value, as well as to variations in the experimental arrangements such as size, shape, and smoothness of the electrodes, proximity of the chamber walls, and voltage wave shape.

Insulating Strength of Freon at High Pressures

That certain compounds in the gaseous state, notably those which contain chlorine, fluorine, or other electronegative atoms, have a higher insulating strength than air or the other permanent gases, has been known since the investigations of Natterer and others in 1898. A number of studies have been made of the insulating properties of Freon 12[9]—a gas which was developed primarily for use as a refrigerant. As seen from figure 1, Freon can insulate a given d-c voltage at about one-third the pressure required with air. It was felt desirable to extend the breakdown studies of Freon to higher pressures and voltages, since the full advantage of such special compounds over air is realized only if they can be used at essentially the same pressures. Figure 3 shows the breakdown strength of Freon in a uniform field for pressures from 5 to 135 pounds per square inch absolute, and with constant potentials up to 350 kv. Since the vapor pressure of this compound at 70 degrees Fahrenheit is about 85 pounds per square inch absolute, the higher pressures were obtained by heating the chamber the required amount. Care was necessary to prevent condensation of the gas on the electrodes, such condensation lowering the voltages which

could otherwise be obtained. A small amount of preliminary sparking was found desirable to condition the electrode surfaces, but the decomposition of the Freon resulting from sparking gradually led to sufficient deposition of carbon on the electrodes to lower the breakdown voltage. This effect was most noticeable at the higher pressures, in which the energy of the discharges was greatest. In general it was found that the behavior of Freon was more erratic the higher the pressure, probably because of the changing nature of the electrode surfaces through carbon deposition and the increasingly high field emission from these surfaces. However, with uniform fields the breakdown gradient continued to increase with pressure, as is shown by the curve in figure 4 for a 0.2-inch gap. Gradients of over 1,200 kv per inch were insulated at 135 pounds per square inch absolute, and there was evidence that with careful electrode conditioning the values indicated by this curve might be increased by about 15 per cent. Figure 5 shows the dependence of the breakdown potential of Freon upon pressure for constant values of pressure times gap. The departure from Paschen's law, as indicated by the slope of these curves, begins when pd is greater than two pounds per inch and increases with the higher values. That this departure progresses more rapidly than in the case of air is probably due in part to the influence of inadequately conditioned electrode surfaces.

Reasons for the Higher Insulating Strength of Freon

The higher insulating strength of Freon and similar compounds, as compared with air and other permanent gases, may be ascribed primarily to two causes. The one is the relatively large number of inelastic impacts which an electron may make in such gases[10] with consequent loss of energy and ionizing power; the other is the electron affinity of the electronegative particles in the gas, such as the chlorine and fluorine atoms. This results in the removal of free electrons from the gas with the accompanying formation of relatively inert negative ions. By the former mechanism, such electrons as are created by ionization in the gas are retarded in their accumulation of ionizing energy by the frequent loss of energy on impact. Through the second mechanism the electrons, which are the most effective ionizing agents, are rendered impotent by attachment to heavy electronegative particles.

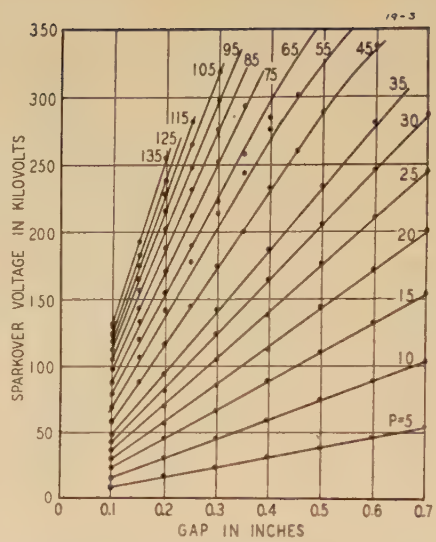


Figure 3. Increase of the d-c spark-over voltage of Freon 12 with electrode separation for absolute pressures from 5 pounds to 135 pounds per square inch. Uniform field

An obstacle to the immediate widespread use of Freon or other such compounds is the gradual decomposition of the gas under the influence of corona and sparkover. In the experimental use of Freon in the pressure-insulated electrostatic generator, although some decomposition of the gas occurred, no impairment of the insulating strength of the gas or of the solid insulation in the chamber, and very little corrosion of the metals was observed after about ten hours. Since there is evidence, however, that the long-time effects of this chemical instability may be serious, this problem and methods of removing the decomposition products of Freon are being studied and will be reported later.

Another limitation to the use of Freon for high-voltage insulation is imposed by the low pressure of 55 pounds per square inch absolute at which the positive point-to-plane breakdown voltage reaches its maximum value.[11] This characteristic, which is common to most gases at ordinary temperatures but which for air and nitrogen occurs at about 100 pounds per square inch absolute, seems at the present time to establish a maximum pressure limit for applications involving highly distorted fields. It thus becomes necessary in applying compressed-gas insulation to electrostatic generators, high-voltage transformers, high-voltage condensers and the like to secure sufficiently uniform fields throughout in order that the pressure of the gas may be fixed by economic considerations rather than by an inherent limitation in its insulating properties.

When it is considered that in many high-voltage applications, such as the insulation of electrostatic generators, any increase in the dielectric strength of the gas is reflected (in the limit) as the cube in reduced volume of apparatus, the great practical importance of such superior insulating gases as Freon is realized. It is not unlikely that compounds will become available which show even greater chemical stability than Freon, and at the same time have higher vapor pressures at room temperature. Such gaseous compounds, whose use for insulation is already in a preliminary commercial stage,[12] may ultimately supplant the permanent gases and even liquid dielectrics for the insulation of high-voltage apparatus.

Acknowledgments

The authors take pleasure in acknowledging the assistance in this work of Mr. A. T. Norton, Jr., as well as of members of the WPA Medical Radiation group. The development of the pressure-insulated X-ray generator was made possible

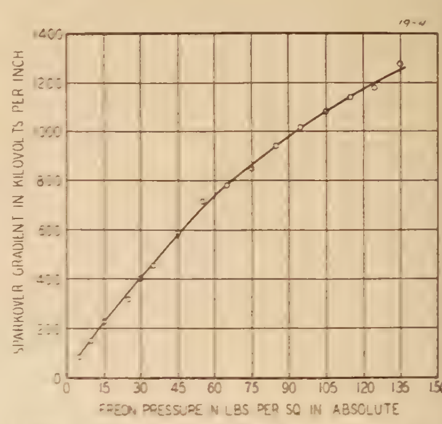


Figure 4. Spark-over gradient in Freon 12 as a function of pressure. Uniform field with 0.2-inch gap

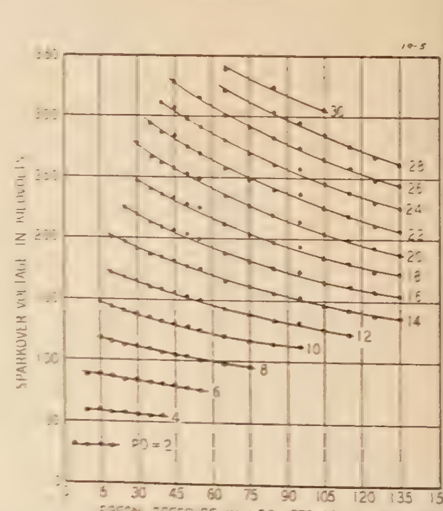


Figure 5. Spark-over voltage of Freon 12 as a function of pressure for several values of pressure times gap in pounds per inch

A Five-Figure Table of the Bessel Function $I_n(x)$

HERBERT B. DWIGHT
FELLOW AIEE

THE modified Bessel function of the first kind, $I_n(x)$, where x is a real quantity, is of widespread application, but it is of particular interest to electrical engineers, since the current and voltage for a traveling wave on an electric line can be expressed as a series of these functions.

A table of these functions was published in the Report of the British Association for the Advancement of Science, 1889, pages 29–32, and has been reprinted in "Bessel Functions" by Gray, Mathews, and MacRobert. While a large number of significant figures were given, the arguments were 0.2, 0.4, 0.6, etc.* The interpolation, as used in engineering work, is somewhat easier and more according to a decimal system when arguments 0.1, 0.2, 0.3, etc., are used. Accordingly, additional values for a five-figure table have been computed, and the enlarged five-figure table is given in this paper.

In a number such as 0.0^826053 in the table, the figure 8 represents the number of zeros before the 2.

The work of computing the new values for this table was done by students under the National Youth Administration at the Massachusetts Institute of Technology, those doing a substantial amount of work including A. L. Carpentier, D. R. Erb, S. Grunes, L. A. King, H. A. Lent, R. P. Mork, R. T. Parry, and B. H. Sexauer.

The values in the table were computed to more decimal places than have been tabulated, and the computations were checked. As a further precaution against errors, columns of differences of the final table were computed and examined for consistency, to a large extent by R. P. Mork, who used the equation

$$\Delta_4 = A - 4B + 6C - 4D + E$$

for the computation of the fourth difference Δ_4 with a calculating machine, where A, B, C, D, and E are any five successive values of $I_n(x)$. This was found to save time and work. See also the introduction to "Tables of the Exponential Function e^x," by WPA of the City of New York, A. N. Lowan, Technical Director. The use of columns of differences is a very searching method of exposing errors in a table.

More than half of the new values were computed by an interpolation method, from the original table mentioned in the second paragraph. Interpolation coefficients given in the paper "Tables and Methods of Extending Tables for Interpolation Without Differences," by George Rutledge and Prescott Crout, *Journal of Mathematics and Physics*, volume 9, 1930, were employed. These, when used with a calculating machine, were found to save considerable work, as no pencil work was needed and no columns of differences of the original table were required. For $x=$ 5.7 and 5.9, Gregory-Newton interpolation coefficients were used, and this gave a comparison of the amount of work by the different methods. For the higher orders, the values were proportionately far apart and the power series in x was used, as follows:

$$I_n(x) = \frac{\left(\frac{1}{2}x\right)^n}{n!}\left[1 + \frac{\left(\frac{1}{2}x\right)^2}{1(n+1)} + \frac{\left(\frac{1}{2}x\right)^4}{1\times 2(n+1)(n+2)} + \cdots\right]$$

Equations for traveling waves on an electric line, which involve Bessel functions of the type $I_n(x)$, are given on pages 161 and 163 of chapter VII of "Principles of Electric Power Transmission," by L. F. Woodruff, and a numerical example is given on pages 163 to 165.

Acknowledgments are here made for valuable help and suggestions from Professors R. D. Douglass, P. Franklin, and L. F. Woodruff.

(For table, see next page.)

Paper 41-6, recommended by the AIEE committee on basic sciences and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted June 25, 1940; made available for preprinting October 25, 1940.

H. B. DWIGHT is professor of electrical machinery at Massachusetts Institute of Technology, Cambridge.

* Large tables of $I_1(x)$ and $I_0(x)$ were given in the Report of the British Association in 1893 and 1896.

---

by a generous grant from the Godfrey M. Hyams Trust.

References

1. ON SOME ELEMENTARY LAWS OF ELECTRICITY, W. Snow Harris. *Philosophical* Transactions of the Royal Society, 1834, pages 213–45.

2. THE GENESIS OF IONS BY THE MOTION OF POSITIVE IONS AND A THEORY OF THE SPARKING POTENTIAL, John S. Townsend. *Philosophical Magazine*, volume 6, 1903, pages 598–618.

3. MECHANISM OF SPARK DISCHARGE IN AIR AT ATMOSPHERIC PRESSURE, I, II, L. B. Loeb and S. M. Meek. *Journal of Applied Physics*, volume 11, 1940, pages 438–47, 459–74. See bibliography.

4. A COMPACT PRESSURE-INSULATED ELECTROSTATIC X-RAY GENERATOR, J. G. Trump and R. J. Van de Graaff. *Physical Review*, volume 55, 1939, pages 1160–5.

5. GENERATING VOLTMETER FOR PRESSURE-INSULATED HIGH-VOLTAGE SOURCES, J. G. Trump, F. J. Safford, and R. J. Van de Graaff. *Review of Scientific Instruments*, volume 11, 1940, pages 54–6.

6. BREAKDOWN STUDIES IN COMPRESSED GASES, A. H. Howell. AIEE TRANSACTIONS, volume 58, 1939 (May Section), pages 193–204. See bibliography.

7. ÜBER DIE ZUM FUNKENÜBERGANG IN LUFT, WASSERSTOFF UND KOHLENSÄURE BEI VERSCHIEDENEN DRUCKEN ERFORDERLICHE POTENTIALDIFFERENZ, Friedrich Paschen. *Wiedemann-Annalen der Physik*, volume 37, 1889, pages 69–96.

8. CONDUCTION OF ELECTRICITY THROUGH GASES (a book), J. J. Thomson and G. P. Thomson. Cambridge University Press, third edition, volume 2, 1933, 608 pages, page 490.

9. DIELECTRIC STRENGTH OF INSULATING FLUIDS, E. E. Charleton and F. S. Cooper. *General Electric Review*, volume 40, 1937, pages 438–42. See bibliography.

10. R. F. Baker and J. T. Tate. *Physical Review*, volume 53, 1938, page 683. An abstract.

11. EFFECT OF PRESSURE ON POSITIVE POINT-TO-PLANE DISCHARGE IN N_2, O_2, CO_2, SO_2, SF_6, CCl_2F_2, A, He, AND H_2, H. C. Pollock and F. S. Cooper. *Physical Review*, volume 56, 1939, pages 170–5.

12. MILLION-VOLT X-RAY OUTFIT, E. E. Charleton, W. F. Westendorp, L. E. Dempster, and G. Hotaling. *Journal of Applied Physics*, volume 10, 1939, pages 374–85.

Table of the Bessel Function $I_n(x)$

x	$I_0(x)$	$I_1(x)$	$I_2(x)$	$I_3(x)$	$I_4(x)$	$I_5(x)$	$I_6(x)$	$I_7(x)$	$I_8(x)$	$I_9(x)$	$I_{10}(x)$	$I_{11}(x)$
0	1.0000	0	0	0	0	0	0	0	0	0	0	0
0.1	1.0025	0.050063	$0.0^{2}12510$	$0.0^{4}20846$	$0.0^{6}26055$	$0.0^{8}26053$	$0.0^{10}21709$	$0.0^{12}15506$	$0.0^{15}96908$	$0.0^{17}53836$	$0.0^{19}26918$	$0.0^{21}12235$
0.2	1.0100	0.10050	$0.0^{2}50167$	$0.0^{3}16708$	$0.0^{5}41750$	$0.0^{7}83472$	$0.0^{8}13909$	$0.0^{10}19866$	$0.0^{12}24829$	$0.0^{14}27585$	$0.0^{16}27582$	$0.0^{18}25073$
0.3	1.0226	0.15169	0.011335	$0.0^{3}56567$	$0.0^{4}21189$	$0.0^{6}63519$	$0.0^{7}15871$	$0.0^{9}33996$	$0.0^{11}63723$	$0.0^{12}10618$	$0.0^{14}15923$	$0.0^{16}21710$
0.4	1.0404	0.20403	0.020268	$0.0^{2}13467$	$0.0^{4}67202$	$0.0^{5}26845$	$0.0^{7}89398$	$0.0^{8}25524$	$0.0^{10}63775$	$0.0^{11}14166$	$0.0^{13}28321$	$0.0^{15}51478$
0.5	1.0635	0.25789	0.031906	$0.0^{2}26451$	$0.0^{3}16481$	$0.0^{5}82232$	$0.0^{6}34212$	$0.0^{7}12205$	$0.0^{9}38108$	$0.0^{10}10578$	$0.0^{12}26430$	$0.0^{14}60041$
0.6	1.0920	0.31370	0.046365	$0.0^{2}46022$	$0.0^{3}34362$	$0.0^{4}20556$	$0.0^{5}10256$	$0.0^{7}43883$	$0.0^{8}16436$	$0.0^{10}54731$	$0.0^{11}16406$	$0.0^{13}44713$
0.7	1.1263	0.37188	0.063790	$0.0^{2}73674$	$0.0^{3}64074$	$0.0^{4}44670$	$0.0^{5}25982$	$0.0^{6}12963$	$0.0^{8}56615$	$0.0^{9}21987$	$0.0^{11}76869$	$0.0^{12}24436$
0.8	1.1665	0.43286	0.084353	0.011100	$0.0^{2}11013$	$0.0^{4}87635$	$0.0^{5}58202$	$0.0^{6}33164$	$0.0^{7}16545$	$0.0^{9}73404$	$0.0^{10}29319$	$0.0^{11}10649$
0.9	1.2130	0.49713	0.10826	0.015972	$0.0^{2}17790$	$0.0^{3}15904$	$0.0^{4}11871$	$0.0^{6}76039$	$0.0^{7}42652$	$0.0^{8}21278$	$0.0^{10}95576$	$0.0^{11}39040$
1.0	1.2661	0.56516	0.13575	0.022168	$0.0^{2}27371$	$0.0^{3}27146$	$0.0^{4}22489$	$0.0^{5}15992$	$0.0^{7}99606$	$0.0^{8}55184$	$0.0^{9}27529$	$0.0^{10}12490$
1.1	1.3262	0.63749	0.16709	0.029891	$0.0^{2}40493$	$0.0^{3}44101$	$0.0^{4}40138$	$0.0^{5}31369$	$0.0^{6}21476$	$0.0^{7}13080$	$0.0^{9}71745$	$0.0^{10}35791$
1.2	1.3937	0.71468	0.20260	0.039359	$0.0^{2}58007$	$0.0^{3}68789$	$0.0^{4}68209$	$0.0^{5}58093$	$0.0^{6}43354$	$0.0^{7}28788$	$0.0^{8}17216$	$0.0^{10}93653$
1.3	1.4693	0.79733	0.24262	0.050815	$0.0^{2}80888$	$0.0^{2}10371$	$0.0^{3}11124$	$0.0^{4}10253$	$0.0^{6}82818$	$0.0^{7}59535$	$0.0^{8}38550$	$0.0^{9}22707$
1.4	1.5534	0.88609	0.28755	0.064522	0.011026	$0.0^{2}15191$	$0.0^{3}17520$	$0.0^{4}17369$	$0.0^{5}15095$	$0.0^{6}11678$	$0.0^{8}81382$	$0.0^{9}51598$
1.5	1.6467	0.98167	0.33783	0.080774	0.014738	$0.0^{2}21706$	$0.0^{3}26777$	$0.0^{4}28406$	$0.0^{5}26426$	$0.0^{6}21885$	$0.0^{7}16331$	$0.0^{8}11088$
1.6	1.7500	1.0848	0.39397	0.099892	0.019371	$0.0^{2}30356$	$0.0^{3}39874$	$0.0^{4}45060$	$0.0^{5}44666$	$0.0^{6}39424$	$0.0^{7}31358$	$0.0^{8}22696$
1.7	1.8640	1.1963	0.45650	0.12223	0.025089	$0.0^{2}41665$	$0.0^{3}58039$	$0.0^{4}69587$	$0.0^{5}73208$	$0.0^{6}68593$	$0.0^{7}57926$	$0.0^{8}44518$
1.8	1.9896	1.3172	0.52604	0.14819	0.032077	$0.0^{2}56248$	$0.0^{3}82798$	$0.0^{3}10495$	$0.0^{4}11677$	$0.0^{5}11574$	$0.0^{6}10341$	$0.0^{8}84091$
1.9	2.1277	1.4482	0.60327	0.17820	0.040545	$0.0^{2}74830$	$0.0^{2}11603$	$0.0^{3}15500$	$0.0^{4}18180$	$0.0^{5}19001$	$0.0^{6}17905$	$0.0^{7}15359$
2.0	2.2796	1.5906	0.68895	0.21274	0.050729	$0.0^{2}98257$	$0.0^{2}16002$	$0.0^{3}22464$	$0.0^{4}27699$	$0.0^{5}30442$	$0.0^{6}30170$	$0.0^{7}27222$
2.1	2.4463	1.7455	0.78390	0.25235	0.062895	0.012751	$0.0^{2}21754$	$0.0^{3}32011$	$0.0^{4}41388$	$0.0^{5}47707$	$0.0^{6}49600$	$0.0^{7}46956$
2.2	2.6291	1.9141	0.88906	0.29763	0.077345	0.016374	$0.0^{2}29195$	$0.0^{3}44923$	$0.0^{4}60761$	$0.0^{5}73288$	$0.0^{6}79748$	$0.0^{7}79029$
2.3	2.8296	2.0978	1.0054	0.34922	0.094415	0.020825	$0.0^{2}38722$	$0.0^{3}62173$	$0.0^{4}87785$	$0.0^{4}11056$	$0.0^{5}12565$	$0.0^{6}13007$
2.4	3.0493	2.2981	1.1342	0.40787	0.11448	0.026257	$0.0^{2}50814$	$0.0^{3}84966$	$0.0^{3}12499$	$0.0^{4}16406$	$0.0^{5}19436$	$0.0^{6}20976$
2.5	3.2898	2.5167	1.2765	0.47437	0.13798	0.032843	$0.0^{2}66033$	$0.0^{2}11478$	$0.0^{3}17560$	$0.0^{4}23978$	$0.0^{5}29557$	$0.0^{6}33199$
2.6	3.5533	2.7554	1.4337	0.54963	0.16537	0.040786	$0.0^{2}85045$	$0.0^{2}15342$	$0.0^{3}24368$	$0.0^{4}34560$	$0.0^{5}44256$	$0.0^{6}51648$
2.7	3.8417	3.0161	1.6075	0.63463	0.19721	0.050313	0.010863	$0.0^{2}20306$	$0.0^{3}33437$	$0.0^{4}49175$	$0.0^{5}65319$	$0.0^{6}79085$
2.8	4.1573	3.3011	1.7994	0.73048	0.23408	0.061686	0.013772	$0.0^{2}26636$	$0.0^{3}45403$	$0.0^{4}69146$	$0.0^{5}95134$	$0.0^{5}11933$
2.9	4.5027	3.6126	2.0113	0.83841	0.27666	0.075204	0.017337	$0.0^{2}34648$	$0.0^{3}61056$	$0.0^{4}96163$	$0.0^{4}13686$	$0.0^{5}17762$
3.0	4.8808	3.9534	2.2452	0.95975	0.32571	0.091206	0.021684	$0.0^{2}44721$	$0.0^{3}81370$	$0.0^{3}13237$	$0.0^{4}19464$	$0.0^{5}26104$
3.1	5.2945	4.3262	2.5034	1.0960	0.38205	0.11008	0.026957	$0.0^{2}57309$	$0.0^{2}10754$	$0.0^{3}18049$	$0.0^{4}27388$	$0.0^{5}37913$
3.2	5.7472	4.7343	2.7883	1.2489	0.44665	0.13226	0.033325	$0.0^{2}72948$	$0.0^{2}14102$	$0.0^{3}24391$	$0.0^{4}38155$	$0.0^{5}54459$
3.3	6.2426	5.1810	3.1027	1.4202	0.52054	0.15825	0.040982	$0.0^{2}92274$	$0.0^{2}18357$	$0.0^{3}32690$	$0.0^{4}52660$	$0.0^{5}77421$
3.4	6.7848	5.6701	3.4495	1.6119	0.60490	0.18861	0.050153	0.011604	$0.0^{2}23734$	$0.0^{3}43470$	$0.0^{4}72046$	$0.0^{4}10900$
3.5	7.3782	6.2058	3.8320	1.8264	0.70105	0.22398	0.061096	0.014512	$0.0^{2}30489$	$0.0^{3}57384$	$0.0^{4}97761$	$0.0^{4}15207$
3.6	8.0277	6.7927	4.2540	2.0661	0.81046	0.26509	0.074109	0.018055	$0.0^{2}38932$	$0.0^{3}75232$	$0.0^{3}13163$	$0.0^{4}21034$
3.7	8.7386	7.4357	4.7193	2.3338	0.93475	0.31273	0.089532	0.022356	$0.0^{2}49431$	$0.0^{3}97992$	$0.0^{3}17595$	$0.0^{4}28859$
3.8	9.5169	8.1404	5.2325	2.6326	1.0758	0.36784	0.10776	0.027554	$0.0^{2}62427$	$0.0^{2}12686$	$0.0^{3}23357$	$0.0^{4}39293$
3.9	10.369	8.9128	5.7983	2.9658	1.2355	0.43145	0.12923	0.033815	$0.0^{2}78443$	$0.0^{2}16329$	$0.0^{3}30805$	$0.0^{4}53115$
4.0	11.302	9.7595	6.4222	3.3373	1.4163	0.50472	0.15446	0.041330	$0.0^{2}98099$	$0.0^{2}20903$	$0.0^{3}40379$	$0.0^{4}71308$
4.1	12.324	10.688	7.1100	3.7511	1.6206	0.58899	0.18404	0.050322	0.012213	$0.0^{2}26620$	$0.0^{3}52620$	$0.0^{4}95115$
4.2	13.442	11.706	7.8684	4.2120	1.8513	0.68571	0.21863	0.061048	0.015140	$0.0^{2}33734$	$0.0^{3}68194$	$0.0^{3}12609$
4.3	14.668	12.822	8.7043	4.7249	2.1115	0.79656	0.25899	0.073805	0.018692	$0.0^{2}42552$	$0.0^{3}87914$	$0.0^{3}16618$
4.4	16.010	14.046	9.6258	5.2955	2.4046	0.92342	0.30598	0.088939	0.022989	$0.0^{2}53438$	$0.0^{2}11277$	$0.0^{3}21779$
4.5	17.481	15.389	10.642	5.9301	2.7347	1.0684	0.36057	0.10684	0.028170	$0.0^{2}66826$	$0.0^{2}14397$	$0.0^{3}28393$
4.6	19.093	16.863	11.761	6.6355	3.1060	1.2338	0.42389	0.12798	0.034400	$0.0^{2}83235$	$0.0^{2}18297$	$0.0^{3}36829$
4.7	20.858	18.479	12.995	7.4195	3.5233	1.4223	0.49719	0.15286	0.041869	0.010328	$0.0^{2}23153$	$0.0^{3}47541$
4.8	22.794	20.253	14.355	8.2903	3.9921	1.6369	0.58191	0.18210	0.050798	0.012768	$0.0^{2}29178$	$0.0^{3}61087$
4.9	24.915	22.199	15.854	9.2575	4.5182	1.8809	0.67967	0.21638	0.061448	0.015730	$0.0^{2}36625$	$0.0^{3}78148$
5.0	27.240	24.336	17.506	10.331	5.1082	2.1580	0.79229	0.25649	0.074117	0.019316	$0.0^{2}45800$	$0.0^{3}99554$
5.1	29.789	26.680	19.326	11.523	5.7697	2.4724	0.92185	0.30334	0.089153	0.023643	$0.0^{2}57069$	$0.0^{2}12631$
5.2	32.584	29.254	21.332	12.845	6.5106	2.8288	1.0707	0.35796	0.10696	0.028852	$0.0^{2}70864$	$0.0^{2}15965$
5.3	35.648	32.080	23.542	14.312	7.3402	3.2324	1.2415	0.42152	0.12800	0.035107	$0.0^{2}87705$	$0.0^{2}20104$
5.4	39.009	35.182	25.978	15.939	8.2686	3.6890	1.4371	0.49538	0.15281	0.042598	0.010820	$0.0^{2}25226$
5.5	42.695	38.588	28.663	17.743	9.3070	4.2052	1.6611	0.58106	0.18202	0.051550	0.013309	$0.0^{2}31545$
5.6	46.738	42.328	31.620	19.742	10.468	4.7884	1.9171	0.68031	0.21633	0.062225	0.016322	$0.0^{2}39319$
5.7	51.173	46.436	34.879	21.959	11.765	5.4466	2.2095	0.79511	0.25657	0.074925	0.019961	$0.0^{2}48854$
5.8	56.038	50.946	38.470	24.415	13.214	6.1890	2.5430	0.92771	0.30367	0.090004	0.024346	$0.0^{2}60519$
5.9	61.377	55.900	42.427	27.136	14.831	7.0259	2.9230	1.0807	0.35872	0.10787	0.029617	$0.0^{2}74750$
6.0	67.234	61.342	46.787	30.151	16.637	7.9685	3.3558	1.2569	0.42297	0.12901	0.035940	$0.0^{2}92070$

Transactions Section

Preprint of Corresponding Pages From the Current Annual Transactions Volume

Any discussion of these papers will appear in the June 1941 "Supplement to Electrical Engineering—Transactions Section"

The Service Factor Rating of Arc-Welding Generators and Transformers

R. C. FREEMAN
NONMEMBER AIEE

A. U. WELCH
ASSOCIATE AIEE

Synopsis: The primary purpose of rating an electrical machine is to give the user an idea of what he may expect from the unit which he purchases.

It is the purpose of this paper to propose a method of rating arc-welding generators and transformers which will give a truer picture of their working ability than is afforded by the present one-hour rating. Such a method of rating will be beneficial both to the customer who buys and uses arc welders and to the manufacturers who produce and market the units. The user will be better able to select a machine which will do the job to be performed, and at the same time he will be assured that he is not purchasing a machine unduly large for his requirements.

The present custom is to give welding transformers and generators a one-hour rating, specifying the current they can deliver for a one-hour period, starting cold, without exceeding the permissible temperature rise. The plan here proposed is to give them a current rating indicative of their normal operating capacity, or short-time welding ability; and an additional service factor rating, indicative of their continuous current capacity, as limited by thermal considerations.

All electric apparatus has these two major limitations on its output, one a "size" limit expressed by breakdown torque, commutation limit, or voltage drop; and the other a thermal limit expressed by the degrees temperature rise permissible for the type of insulation used. These two limits are usually quite independent of each other, so that no single number, such as a one-hour rating, can fully describe the usability of the apparatus. The proposed service factor rating gives both of these limits, and therefore gives the user the data for applying the apparatus to a variety of duty cycles.

In conclusion, it is suggested that welding generators and transformers be designed for a service-factor rating of 75 per cent, since this corresponds best to typical welding duty cycles. It is also proposed that the standard AIEE values of temperature rise by resistance for continuous rated machines, 60 degrees centigrade for class A, or 80 degrees centigrade for class B insulation, be recognized as the limiting values in continuous operation at the service-factor rating.

Paper **41-33**, recommended by the AIEE committee on standards and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 22, 1940; made available for preprinting December 7, 1940.

R. C. Freeman is in the motor engineering department of the General Electric Company, Lynn, Mass., and A. U. Welch in the power transformer engineering department, General Electric Company, Pittsfield, Mass.

1. For all numbered references, see list at end of paper.

Rating for Welding Service

BEFORE proposing a method of rating, it is advisable to consider the purpose of rating. "The rating of a machine or other equipment is a set of performance characteristics which are subject to verification by test under specified conditions and which by mutual agreement between buyer and seller may serve as a basis of specifications and contracts covering the purchase and sale of the machine or other equipment. The rating is used by the manufacturer in the design and fabrication of the equipment and is used by the purchaser as the basis for application; therefore, the terms in which the rating is stated should be definite, easily verified, of such a nature as to permit intelligent use of the equipment, and as far as possible inclusive of usual conditions as found in practice."[1]

A common sense approach to the problem requires consideration of three different factors:

1. A rating suited to typical welding duty cycles, indicating electrical and thermal limitations.

2. A method of temperature measurement that will give the best indication of actual insulation temperature.

3. Selection of temperature-rise limits to assure satisfactory life of the machine as well as effective use of material in its construction.

In general, there are two types of duty to which an arc-welding generator or transformer may be subjected: Hand welding duty, and automatic welding duty. Because of the infinite variety of hand welding jobs, the duty cycle of such work varies from below 25 per cent up to as high as 75 per cent or 80 per cent of the total elapsed time in the case of production line work. In the case of intermittent welding done in automatic installations, the duty cycles may equal those in the upper brackets of hand welding operation. In a small percentage of cases such as pipe welding and other long seam welding, the length of the arc time may be so long that the application requires a continuous rated machine.

Standards[1] for rating arc-welding transformers and generators now specify temperature rise to be measured by operating the machine at rated current continuously for one hour (one-half hour for the smaller sizes), starting cold. There is also included a statement that transformers should be capable of carrying 75 per cent of rated current continuously. The emphasis has been placed on the one-hour rating and most purchasers, even those having strict specifications of their own, have paid little attention to the continuous capacity, but have required test only at the one-hour rating.

Disadvantages of a Short-Time Rating

In order to illustrate clearly the shortcomings of a short-time rating for machines which must carry cyclic loads, we have borrowed two hydraulic analogy diagrams from L. E. Hildebrand's paper on "Duty Cycles and Motor Rating."[2]

Figures 1 and 2 present hydraulic analogies of temperature rises in two electrical machines. Water flowing into the tank represents motor losses—the smaller stream represents no load losses and the larger stream stands for additional losses under load. The height of water in the tank is analogous to temperature rise, while the capacity of the tank is analogous to the heat storage capacity of the machine. The outlets at the bottom of the tank illustrate heat dissipation.

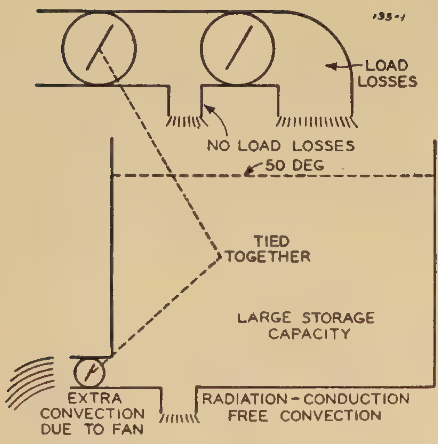


Figure 1. Hydraulic analogy

Short-time rated machines
Poorly ventilated

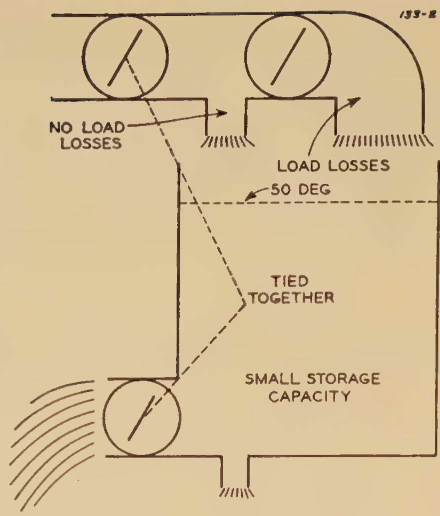


Figure 2. Hydraulic analogy

Short-time rated machines
Well ventilated

In these two diagrams the losses in the two machines are the same. However, in the machine shown in figure 1 we find that the heat dissipating ability as illustrated by the size of the outlet is small, while the thermal capacity of the machine as indicated by the volume of the tank is large; so that in the period of one hour the level of the temperature will just reach a point of 50 degrees rise.

In the case of the diagram in figure 2, we find a machine with a much smaller thermal capacity which is illustrated as a smaller tank. It is only as a result of the large heat dissipating ability as illustrated by the large outlet pipe that this machine is able to run for a period of one hour without exceeding the temperature rise of 50 degrees. Thus, here we have two machines both of which will meet identically the same one-hour load rating specification. But if we were to hold these two machines on a duty-cycle basis all day, we would find a great difference in their operation. The machine represented by the diagram in figure 1 has small heat dissipating ability; therefore, during periods of no load, heat is dissipated from this machine very slowly. During a day's welding, we find that the level of temperature rise continues to climb and may far exceed that obtained on the constant load during the one-hour period.

On the other hand, as soon as the load is removed from the machine represented by the diagram in figure 2, we find that heat is drained rapidly from that machine as a result of the high heat dissipating ability of that unit. With heat being thus quickly and efficiently removed, this unit can run all day on a duty-cycle load and will likely not even reach the level of temperature rise indicated at the end of a one-hour period.

Figure 3 illustrates these points in terms of specific transformer designs. In the figure, curve B_1 is the heating curve of a transformer with a one-hour rating. This same transformer carrying welding load will heat as in curve B_2, if designed with adequate cooling.

However, a transformer could be built with insufficient cooling which would match the one-hour heating curve B_1 but would heat under welding load as in curve B_3. Such a transformer would run considerably over its rated temperature rise on a long-continued load, such as a half a day's work. A transformer designed with heavy copper coils at low current density without adequate ventilating ducts, or a transformer with windings wound close on the core to allow coil heat to be absorbed by the slowly heating core, would meet the one-hour temperature rise but would run hot on actual welding service.

On the other hand, a transformer can be built with heating curves similar to A_1 and A_2. This transformer would reach rated temperature rise in only one-half hour on the short-time test at continuous rated current (curve A_1), but would operate well under rated temperature rise on all-day welding duty as shown by curve A_2. Also, its quick cooling after removal of load (end of curve), would compensate for its quicker heating time by reducing the total time at high temperature.

It can thus be seen that a properly designed transformer rated for a half-hour short-time test may be better than a poorly designed unit which meets the one-hour test. This is the most important reason why a short-time rating may be meaningless. The short-time rating is artificial, does not take into account the important consideration of all-day operation, and does not tell the operator what he can obtain in actual service without injury to the transformer.

Another drawback to the short-time rating is the difficulty of obtaining accurate tests. The problems involved in starting cold, adjusting load accurately and quickly, and timing accurately are serious and make the tested temperature rise obtained doubtful, especially if thermometers are used.

Continuous Ratings

One alternative method of rating is to rate the welding generator or transformer in terms of its maximum continuous current obtainable without exceeding rated temperature rise. This is done to a considerable extent in Europe. Continuous rating suffers from the disadvantage that it does not tell the operator what current he can obtain while welding—always more than the continuous current—since all welding operations are inherently discontinuous loads.

Typical Duty Cycles

In manual welding there is no such thing as a continuous load. In hand welding the maximum time on without interruption is short, about two minutes, the time for one stick of electrode to be consumed. After one electrode is consumed the operator must raise his hood, remove the end of the consumed electrode, insert the new electrode, position the electrode, lower the hood, and restart the arc. This operation consumes time at least equal to ten per cent of the arc time. However, there are always other operations required, such as change or reposition work, chip slag, add parts, change current, rest and delay.

From a careful study of many types of hand welding operations, the writers have come to the following conclusions:

Many welding duty cycles average about 25 per cent.

On highly repetitive work the duty cycle may rise to about 50 per cent. One such cycle is shown in table I in this paper, and is followed by a similar but simplified cycle, table II, which was used as the basis of a heating test. The curve of temperature rise on this test is shown in figure 4. This particular test was made on a large fan-cooled welding transformer.

Exceptional welding jobs have been found with as high as 72 per cent duty. One such is shown in table III. This shows a time study of a job requiring 63 minutes total. However, there was permitted the welding operator an additional 15 per cent time for rest and delay not shown in the table

which would reduce the duty considerably. It seems probable that 70 per cent approaches the maximum duty cycle which can be obtained in long-continued manual welding.

Other Factors Affecting Heating

Since most arc-welding transformers and generators are furnished in standard ratings and are not built to the exact rating needed for a particular job, the factors of overload and underload should also be considered. The overload range of arc-welding transformers is not very large, generally about 25 per cent. Further overload is prevented by the limit of reactance or other type of current control. Here again proper information on the duty-cycle curve in the hands of the operator would be of value, permitting him to keep within safe temperatures by controlling the duty cycle on those jobs where the overload range is used.

It can safely be expected that in the vast majority of applications the machine will be operated at less than rated current. The range of current obtainable at welding voltages generally goes down to 20 per cent of the rated current in order that one machine may be capable of doing a wide variety of work. In many jobs it is necessary to change current several times to accommodate the different sizes of electrodes required to weld an assembly. However, it is necessary to rate the generator or transformer on a reasonably high duty cycle at its rated current for the rating implies that the equipment may be used for the vast majority of welding operations at that current. Nor is it fair to make the standard duty cycle so low as to deprive the user of any increased life he may obtain when using the machine at less than rated current.

Table I. Typical Heavy Duty Cycles—Hand Arc Welding

Minutes on	Minutes off
	1.93
1.85	0.49
1.85	0.49
1.85	0.60
1.17	3.33
2.16	0.49
0.61	1.68
0.26	0.35
Total 9.75	9.36
Duty cycle 51%	

Table II. Typical Heavy Duty Cycles—Hand Welding

Minutes on	Minutes off
	2
2	0.5
2	0.5
2	0.5
1	3.5
2.5	0.5
0.5	1.5
0.75	1.25
Total 10.75	10.25
Duty cycle 51%	

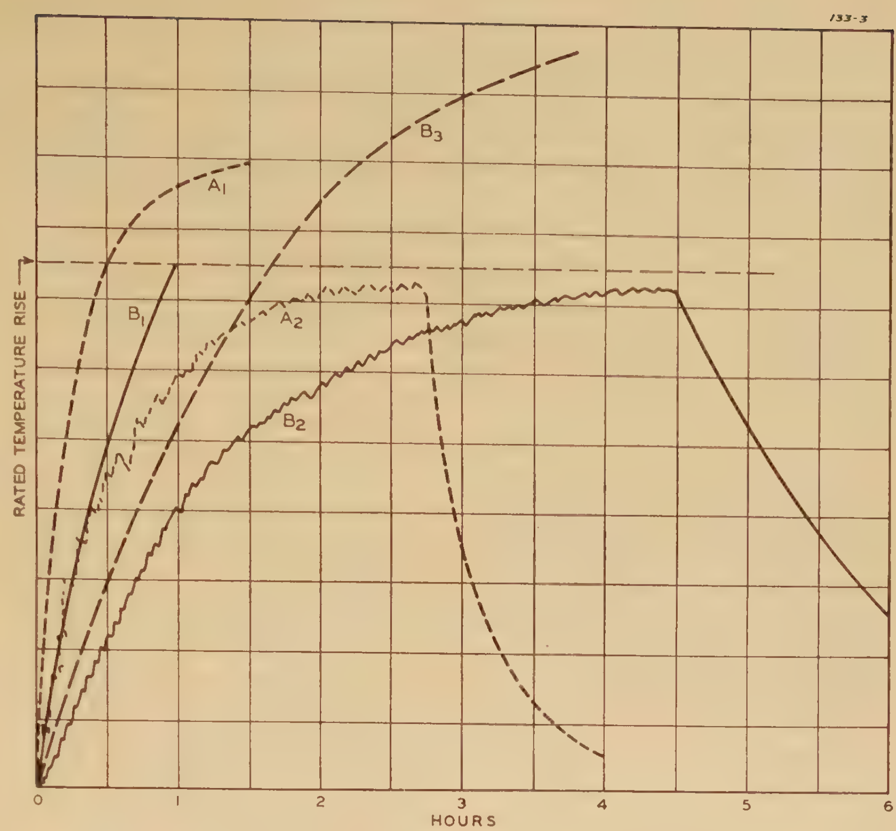


Figure 3. Heating curve

Arc-welding transformer
A—Transformer with low heat storage (half-hour rated)
A_1—Continuous at rated current
A_2—At 60 per cent welding duty cycle
B—Transformer with high heat storage (one-hour rated)
B_1—Continuous at rated current
B_2—At 60 per cent duty cycle (well ventilated)
B_3—Average at 60 per cent duty cycle (poorly ventilated)

Suggested Duty-Cycle Standard

When all the above factors are taken into consideration, the authors feel that a standard duty cycle for rating arc-welding generators and transformers should be 60 per cent. A machine thus rated would carry the vast majority of hand welding operations without exceeding rated temperature. Also, since most welding operations do not exceed 50 per cent time on, a reasonable margin is left for operation at some overload. A maximum time on of six minutes out of ten would insure adequate heat storage capacity.

There is precedent for a duty-cycle rating in welding. All resistance-welding transformers are now rated on a duty-cycle basis, the standard being 50 per cent.

The most comparable test would be of course, a duty-cycle test with the generator or transformer continuously excited and alternately loaded for six minutes and open-circuited for four minutes. This test would result in a saw-tooth shaped temperature curve. Such a test is rather difficult to make due to the problem of accurate timing, but it is provided for in the VDE (German) motor standards. Special arrangements might have to be made to test welders where output current is controlled by taps, rather than by adjustable magnetic means, in order to make sure that each winding is properly heated.

Service-Factor Rating

On the assumption that the temperature rise varies as the square of the load current, a duty cycle with 60 per cent time on would give the same heating as a test with $\sqrt{0.60}=0.775$ current continuously. For the sake of simplicity, therefore, it is suggested that the standard temperature-rise test should consist of a continuous heat run at 75 per cent of rated current, carried on until the temperature rise becomes constant. This test will definitely fix the capacity of the machine on a 100 per cent duty cycle, or

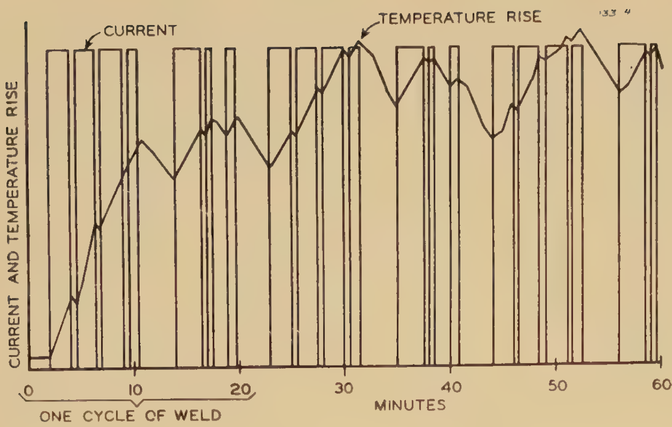


Figure 4. Heating curve

Arc-welding transformer

(51 per cent welding duty cycle)

continuous service, and it also avoids all the difficulties inherent in making transient temperature measurements. Furthermore, the temperature-rise limit to be prescribed for this continuous test will logically be the same as dictated by experience for all other types of continuous rated apparatus, giving the maximum simplicity in standards.

This 0.75 ratio of permissible continuous output to the rated capacity is called the service factor, as it corresponds to the definition of service factor that has long been used for general-purpose motors. Such motors have 40-degrees-centigrade rise at their rating, and a service factor of 1.15, corresponding on the average to the increased load at the 50-degrees-centigrade rise value permissible for continuous rated apparatus in specific applications.[3]

It has already been suggested by L. E. Hildebrand that service factor ratings of less than unity should be used for high torque motors on intermittent duty cycles, instead of the customary short-time ratings.[2] The same reasoning outlined in the preceding paragraphs applies to a wide variety of apparatus in intermittent use. In each case the nameplate rating should be indicative of the safe allowable load for a particular kind of duty, and the service factor indicates the permissible continuous, or rms, load.

On the several grounds of convenience, testing accuracy, and versatility of application, therefore, the service-factor rating method is suggested as preferable for welding transformers and generators; and the specific value of 75 per cent service factor is suggested as most suitable for usual arc-welding service.

Automatic Welding

All the foregoing discussion refers to hand welding, that is, welding with the electrode holder in a man's hand. No attempt will be made in this paper to recommend duty-cycle ratings for automatic machine welding. Many machine welding installations operate at very low duty cycles since it often takes longer to load and align the work in the machine than to make the weld. Many other installations, particularly where one transformer is switched alternately between two welding machines, one welding while the other is loading, operate at very high duty cycles, on the order of 80 per cent or higher. Fortunately, it is not so important to have a standard for such installations since they usually represent such large investments as to justify individual study and application.

Temperature-Rise Measurement

The aim of temperature-rise measurement is to determine the hottest temperature reached by the insulation, in order that long life of the machine may be assured.

The three general methods of temperature measurement are: The measurement of the temperatures upon external parts of windings or core by thermometer or thermocouple, measurement from the cold to hot resistance change of a winding, or the use of embedded detectors.

As a result of the demands of the industry for easily portable arc-welding sets, the trend of generator designs is to small machines which are very well ventilated. The fact that these units are so well ventilated by an air blast means that there is, of necessity, a greater thermal gradient from the inside of the coil winding to the external surface of the insulation. This means that surface temperatures vary widely from internal temperatures and that the extent of this variation is influenced considerably by the method of ventilation employed.

It is very difficult to get accurate transformer temperatures by thermometer or thermocouple unless thermocouples are actually built into the winding. In most natural draft transformers, particularly those with heavy coils, a thermometer or thermocouple on the outside of the coil may read 20 to 30 per cent lower than the average temperature rise of the winding. The rise by resistance method, of course, becomes mandatory in oil or synthetic fluid-immersed transformers since it is then practically impossible to insert thermometers or thermocouples.

While the embedded detector method is of unquestioned desirability in heat flow tests, its use in commercial testing is pretty much out of the question.

A combination of the inadequacy of surface temperature measurements with the difficulty of making embedded detector measurements leads us to the measurement of temperature rise by the resistance method. By the resistance method, it is possible to obtain a true average winding temperature regardless of whether the coil is exposed to a blast of cooling air or whether it is well wrapped up in electrical and thermal insulating material. Although this method will, of course, not give an actual hot-spot temperature indication, yet it will be a much more reliable indication of the hot-spot temperature than any surface temperature measurement.[4]

As an aid in attaining a true indication of temperature rise, we will find that the adoption of the duty-cycle or service-factor method of rating is of considerable help. With short-time periods of test the rate of rise of internal temperatures may be so great that measurements of a final surface temperature are likely to be very inconsistent and consequently therefore, also inaccurate. While it is a fact that a true sportsman will not shoot at a standing bird, fortunately there is no sporting or ethical principle which requires the builders of arc-welding equipment to attempt to measure temperature rise "on the wing." With the adoption of the service-factor method of rating welders it will be possible to allow the temperature of the machine to reach a state of equilibrium and thus allow accurate measurement. The combination of service-factor rating with temperature rise by resistance measurement will assure us that we do not have our heads in the sand but that we will actually know the average temperature rise of the windings in our arc-welding machines. To know the true values of temperature rise is of unquestioned advantage for both the user and the manufacturer of welding machines. The manufacturer can know that he is making optimum use of all of the material within the machine without exceeding safe temperature limits; while the purchaser will be assured of long life machines giving trouble-free operation.

Limiting Temperature Rise

The two important factors governing the life of insulation are maximum temperature and the length of time the insulation is hot.

The maximum permissible operating temperature of the insulation is a function of the type of insulation, both fibrous materials and impregnating compounds. The general subject of insulation characteristics is too long to discuss here, so for the purpose of this paper it will be assumed that the commonly accepted standards[4] will insure satisfactory life of insulation, and that these rises should not be exceeded except for very short intervals of time.

For a given temperature, the life of insulation is reduced more or less directly with time; that is, if a transformer were hot only one-fifth of the time, its insulation could be expected to last five times as long as one hot continuously. For class *A* insulation it has been shown[5] that within limits the life of insulation is reduced roughly 50 per cent for each 8- to 12-degree increase in temperature. Therefore, the life reduction, in aging units, can be approximately estimated in the form of an exponential function of temperature, multiplied by the length of time the temperature persists in the insulation. For class *B* insulation, such as is used in most arc-welding transformers, the rate of aging has not yet been determined; however, it undoubtedly follows some similar law but probably with a higher temperature increment for a given aging.[6]

From the foregoing factors it will be seen that the shapes of the heating and cooling curves of a welder affect insulation life. For example, a welder which heats slowly may have the advantage of slow heating offset by cooling more slowly and thereby keeping its insulation hot longer than a welder which heats and cools quickly.

Since the present NEMA standards for welding generators require measurement of temperature rise by thermometer, it is pertinent to inquire what the corresponding values of rise by resistance are for actual machines now in use. As pointed out previously, and recognized in the AIEE "General Principles Upon Which Temperature Limits Are Based in the Rating of Electrical Machinery and Apparatus," there is a considerably greater difference between the two methods of measurement for highly rated direct-current machines than the ten-degree-centigrade value usually assumed for class *A* insulation. With the forced draft ventilation commonly in use on arc-welder sets, the thermal gradient between the inside windings and the outside of the coils is so great that the actual excess of the rise by resistance over that by thermometer is often 20 degrees centigrade or more.

Depending upon the thickness of insulation over the windings and the intensity of the blast of ventilating air, it is a matter of test record that temperatures measured by the resistance method range from 17 to 42 degrees higher than the values read by thermometer or thermocouple at the outer surface of the coils.

In view of the intermittent character of hand welding, and the satisfactory service records of welders having these relatively high internal temperatures under rated load conditions, it is permissible to set considerably higher limits for temperature rise for short-time rated than for continuous-rated machines. For example, the latest NEMA welding standards[1] permit 100-degrees-centigrade rise by thermometer, or 125 degrees centigrade by resistance, for "class *BB*" insulated welders rated on a half-hour or one-hour basis. Presumably this insulation is similar to the special class *B* insulation used in railway motors, for which 120-degrees-centigrade rise by resistance is permitted.[7] However, as previously indicated, the typical welding duty cycle of 60 per cent time on and 40 per cent time off with a time cycle of only a few minutes, results in no greater operating temperature than would be caused by a continuous load of about 75 per cent of the short-time rated amperes. And, to assure the service life normally expected of electrical apparatus, this average operating temperature should not exceed the standard limiting values for continuous-rated machines, which are: For class *A* insulation, 50 degrees centigrade by thermometer or 60 degrees centigrade by resistance, and for class *B* insulation, 70 degrees centigrade by thermometer or 80 degrees centigrade by resistance.[12] Thus, the 75 per cent service-factor rating method with the standard continuous-temperature limits is a logica outcome of the recent trends in welding transformers and generators.

Conclusions

After consideration of all these factors, it is recommended that welding generators and transformers be given a nameplate rating representative of their expected normal welding currents, as at present, and in addition a service-factor rating of 75 per cent. Acceptance tests would then include a continuous test run at 0.75 of the nameplate amperes without exceeding a limiting temperature rise by resistance of 60 degrees centigrade for class *A* insulation or 80 degrees centigrade for class *B* insulation; or corresponding values of 50-degrees-centigrade and 70-degrees-centigrade rise if the thermometer method of measurement is used.

Table III. Typical Heavy Duty Cycles—Hand Welding

Minutes on	Minutes off	Minutes on	Minutes off	Minutes on	Minutes off
	2.07	1.24	1.72	0.66	2.92
1.54	0.19	0.90	0.19	2.70	0.19
1.54	0.19	0.90	0.19	0.34	0.19
1.54	0.19	0.90	0.19	0.34	0.19
1.54	0.19	0.90	1.32	0.34	0.19
1.54	0.19	0.90	0.19	0.34	0.19
1.54	0.19	0.90	0.19	0.34	0.19
1.54	0.19	0.90	0.19	0.34	0.19
1.54	0.19	0.90	0.19	0.34	0.19
1.54	0.19	0.90	0.19	0.34	0.19
1.54	0.19	0.90	0.19	0.34	0.60
1.54	0.19	1.24	0.85	2.37	0.44
1.54	0.19	0.66	0.19	2.37	0.18
1.54	0.70	0.66	0.19		
1.24	0.19	0.66	0.19		
Total				45.88	17.26
Duty cycle				72.7%	

References

1. Electric Arc-Welding Machine and Electrode Standards, NEMA, Publication No. 40-62, October 1940.

2. Duty Cycles and Motor Rating, L. E. Hildebrand. AIEE Transactions, volume 58, 1939 (September section), pages 478–83.

3. Rating of General Purpose Induction Motors, P. L. Alger and T. C. Johnson. AIEE Transactions, volume 58, 1939 (September section), pages 445–59.

4. General Principles Upon Which Temperature Limits Are Based in the Rating of Electrical Machinery and Apparatus, AIEE Standards No. 1, June 1940.

5. Loading Transformers by Temperature, V. M. Montsinger. AIEE Transactions, volume 49, April 1930, pages 776–92.

6. Application of Class B Insulation to Auxiliary Type D-C Motors in Severe Duty Service, F. A. Compton, Jr. AIEE Transactions, volume 59, 1940, pages 828–34.

7. American Tentative Standards for Railway Motors and Other Rotating Electrical Machinery, AIEE Standards No. 11, March 1937.

Engineering Requirements for Program Transmission Circuits

F. A. COWAN
MEMBER AIEE

R. G. McCURDY
FELLOW AIEE

I. E. LATTIMER
MEMBER AIEE

Synopsis: Present-day program networks are reviewed from the standpoints of engineering, design, and operation as developed to meet the needs of the broadcasters. The factors requiring consideration in the further development of program networks in anticipation of future needs are also discussed. The presentation of the paper is supplemented by a demonstration of the quality obtainable by transmission over various types of telephone facilities.

Introduction

THE growth of radiobroadcasting to the magnitude of a major national industry within the last 20 years has been accompanied by the development of a nation-wide system of wire-line networks interconnecting hundreds of broadcasting stations. Papers have been presented before this Institute from time to time[1,2,3] describing the types of plant used for these networks and discussing important features of their design and operation. With these 20 years of experience as a background, it should now be of interest to review how the various requirements of broadcasting have influenced the development of the networks and to consider some of the factors which have determined the point to which transmission and operating features have so far been carried.

Simply stated, broadcasting is a means by which sounds originated at one place are reproduced simultaneously to large numbers of listeners distributed over wide areas. The simplest possible radiobroadcasting system would consist of a microphone, a radiobroadcast transmitter and some radio receiving sets. Such a system could serve only the listeners within the comparatively limited service area of the transmitter. To serve the whole nation many transmitters must be established about the country. Furthermore the most desirable sources of program are not usually in the neighborhood of the transmitter to which a particular listener can tune, since talent tends to be concentrated in certain parts of the country, and special events of interest may occur anywhere. To give a true country-wide service so that every listener can hear the programs he enjoys wherever they may originate, a supplementary transmission system must be provided, interconnecting the many studios and broadcasting stations. The wire networks that perform this function comprise the subject matter of this paper.

The present extent of the wire-line facilities which are associated with the major portion of these networks is indicated in figure 1. The width of the lines on this chart has been made proportional to the numbers of circuits in the various sections. The total length of these circuits is in excess of 110,000 miles, and it is not unusual for a program originating at some point on a network to traverse more than 7,000 miles of circuit before being broadcast by the most remote station.

The requirements which the program networks must meet are in the final analysis determined largely by the needs of the broadcasters. The objective of a program network service is to meet these needs in as complete and prompt a manner as possible consistent with reasonable cost. With this objective in mind, it is necessary in planning the plant to consider not only the day-to-day needs, but the possible future needs as well. The importance of this may be appreciated when it is considered that plant provided today for program transmission service will need to be adaptable to the service requirements 10 or 20 years hence. As a result of such planning, cables and equipment installed 5, 10, and 15 years ago, meet present-day requirements, and with some rearrangements, will take care of those likely to develop tomorrow.

The detailed planning of program transmission circuits requires consideration of:

1. The numbers of circuits likely to be required, section by section, over each route;
2. The provisions for reliability, flexibility, operation, and supervision essential to a high-grade network service;
3. The transmission requirements, or electrical characteristics, necessary to achieve a natural reproduction of the program.

These three general classes of requirements will be considered in order.

Number of Circuits Required

The circuits which have been established on a full-time basis for continuing use form the backbone of the program networks. Even for these circuits, however, permanence is relative since frequent extensions and rearrangements are made to meet changing requirements of the broadcasters. Aside from these full-time circuits there are intermittent requirements occasioned by special events and other short-period needs of the broadcasters, some of which involve networks almost as extensive as the full-time networks. In addition reliability of service requires provision for rerouting the networks in the event of trouble. Figure 2 shows the year-by-year growth in the operated mileage of program circuits for the period 1926 to 1940. Of the more than 110,000 miles of circuits shown for 1940, about 45,000 miles have been provided for the short-period services and as stand-by facilities for protection. In addition to these, there are still other circuits, normally assigned to other services, which are arranged to be readily adaptable to program service to supplement the reserve facilities maintained on a full-time basis.

The time interval necessarily accompanying any extensive construction project makes it necessary to engineer plant considerably in advance of actual service requirements to meet, not only the expected growth, but also the changes in network routing. Figure 3 shows for two typical sections along major routes the variations in requirements for full-time network circuits resulting from growth and rearrangements required by the broadcasters. While, in planning to meet these rapid variations in circuit requirements, advantage can be taken of some latitude which exists in the choice of routes for occasional services and protection facilities, the task of balancing the provision of circuits against requirements is an entertaining and at times difficult one for the circuit engineer.

Operating Requirements

Considering for a moment the variety of programs originating at many different

---

Paper 41-41, recommended by the AIEE committee on communication and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 27, 1940; made available for preprinting December 10, 1940.

F. A. Cowan is transmission engineer, and I. E. Lattimer transmission methods engineer, for the American Telephone and Telegraph Company, New York, N. Y., and R. G. McCurdy is director of transmission engineering, Bell Telephone Laboratories, New York, N. Y.

The authors of this paper gratefully acknowledge the assistance in its preparation of many of their associates, especially W. E. Bloecker, D. K. Gannett, and G. S. Bibbins.

1. For all numbered references, see list at end of paper.

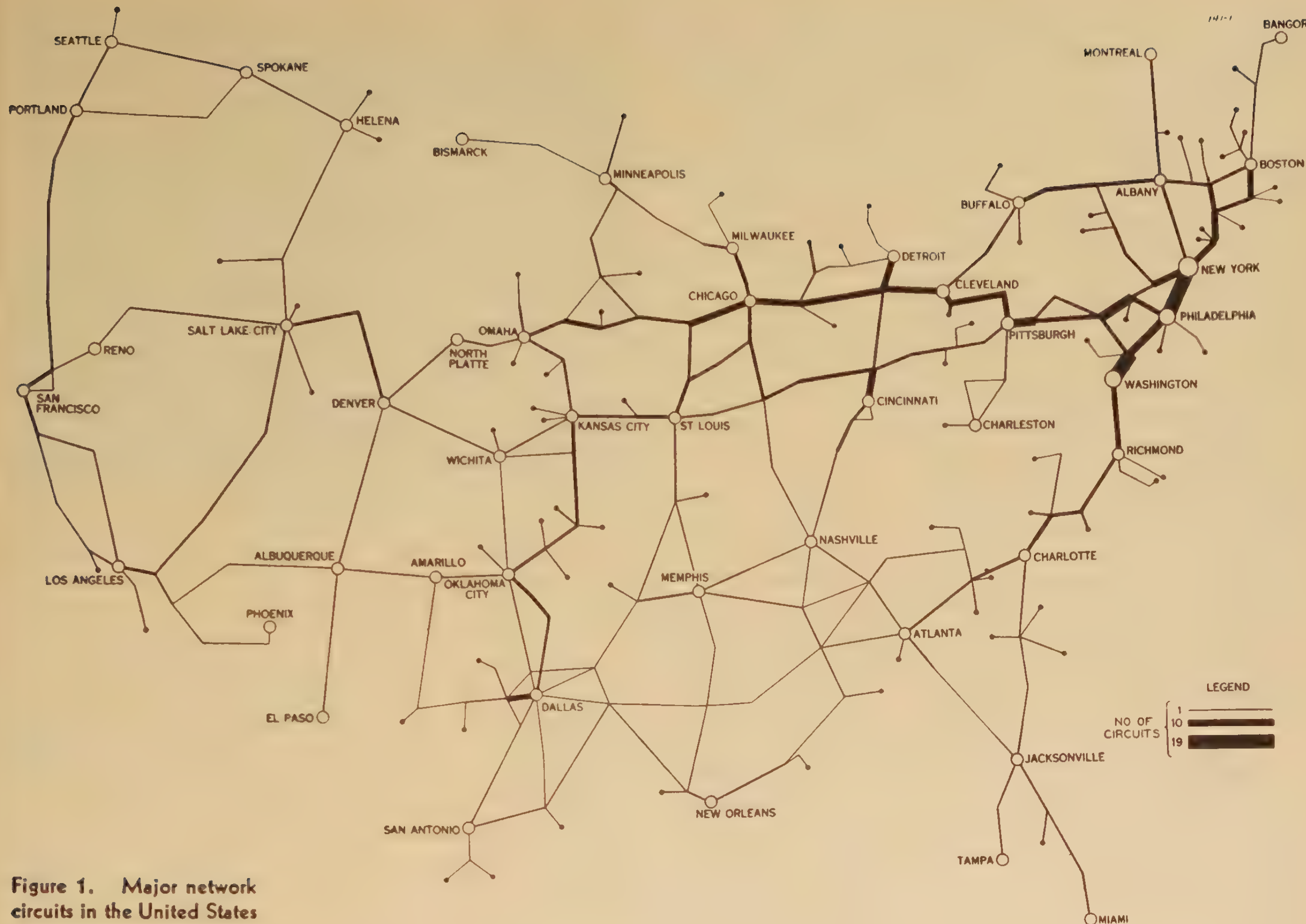


Figure 1. Major network circuits in the United States

points that can be heard on any home radio set in the course of an evening without once changing the tuning, it will be apparent that minute-to-minute rearrangements of an established interconnecting network must be possible. For example, studios have to be changed from receiving to originating, sections of the network have to be made to transmit first in one direction and then in the other, and branches have to be connected and disconnected. These changes in the network have to be made in the few seconds elapsing between the close of one program and the start of the next on the receipt of selected cue words or sounds. Even during the course of a single program, switches or reversals may have to be made to change the originating point temporarily. To provide for these rapid changes, special operation and special switching and reversing equipment are required at many points along the network. Much of this equipment is under remote control from selected points.

The greater portion of the switching of program circuits is done at about 25 points throughout the country on the major networks. On the average more than 25,000 switching operations per month are performed at these 25 points. During the busy hours of any typical evening there may be something over 500 men on duty at all of the offices about the networks.

At points where switching requirements are simple, the switching equipment consists merely of a few keys. At the larger points where the switching requirements are complex, the switching equipment consists of elaborate relay and control arrangements. These are so designed that it is possible to set up in advance the circuit combinations required for the ensuing program period without disturbing the programs in progress. The actual switching operation takes place at the instant the monitoring attendants signal the receipt of the last of selected cues, and not before then. This type of arrangement affords a maximum of protection against error, as it is possible to check the presetting for the next switch or make a last minute change if necessary any time before the switch has been made.

Figure 4 shows a picture of such a switching arrangement in use at Omaha, Nebraska for one broadcasting company.

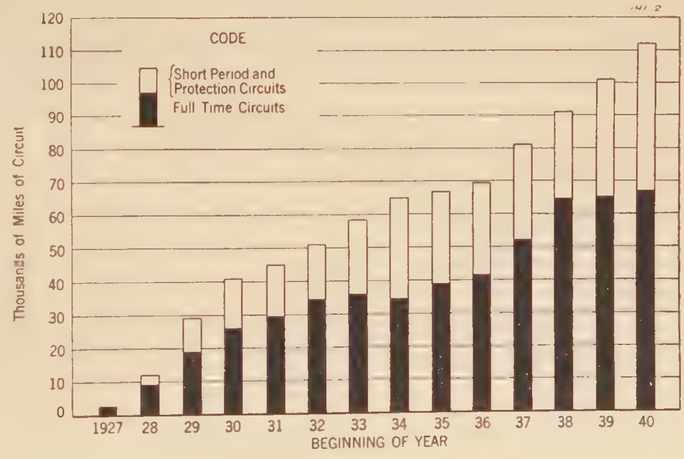


Figure 2. Growth in mileage of major network circuits

At this point 13 circuits used in various trunk and branch sections of two networks are connected to the switching equipment. These are grouped in various combinations to take care of as many as five simultaneous programs. A maximum of five cues might, therefore, be involved in a switch at this point.

The operation and maintenance of the networks are carried out by a special organization under centralized authority and trained in the application of uniform methods and procedures found by experience to be productive of best results. Transmission is monitored continuously at strategic points about the networks. In order to facilitate the activities of this group many thousands of miles of intercommunicating telephone and telegraph circuits are provided full time for their use.

A picture of a monitoring position in the program transmission office at Washington, D. C. is shown in figure 5. It will be noted that the monitoring attendant is using an individual headset. This is of a special high fidelity type and is used to avoid the confusion that would result from attempting to monitor a number of different programs simultaneously with loud-speakers. Loud-speakers are available, however, for supplementary checks of quality whenever required.

Accurate transmission measuring equipment is necessary at the various operating points about the networks to insure satisfactory transmission maintenance results.

Transmission Requirements

The general transmission requirement for a broadcasting system is that the program material be transmitted with a high degree of naturalness. Although the exact determination of the transmission characteristics which would accomplish this involves many considerations it will be assumed in this discussion that an ideal transmission system is one in which the sound waves impressed on the listeners' ears in the home are an exact replica of the sound waves striking the microphone in the distant studio. Limitations inherent in the human ear, in the program material to be transmitted, and in the usual listening conditions, however, make such ideal transmission unnecessary. In expressing the requirements for satisfactory transmission, frequency range, attenuation distortion, delay distortion, nonlinearity and noise are used as indices of quality.

Before taking up the transmission requirements of a program circuit, it is important to consider further the fundamental factors that are involved in fixing the characteristics considered desirable for the entire system. According to Harvey Fletcher,[4] the zone of audibility of the average normal human ear for pure or single frequency sounds is the area within the curve of figure 6. The abscissas represent frequency and the ordinates show the range of intensity recognizable as sound, between the lower limit or threshold of audibility and the upper limit where the sensation of pain is felt. It is seen that the extreme frequency range shown on the chart is from about 20 to 20,000 cycles per second. This range is for young people. It is considerably less for middle-aged and elderly people, and varies with individuals.

In addition to the limitation of the ear there is the fact that there is little energy present in most program material in the extremes of this range, particularly in the upper frequencies. The energy versus frequency spectra of music and other forms of program have been published elsewhere.[5] Figure 7 shows the frequency range which must be transmitted for a number of instruments, speech, and certain noises, so that competent observers cannot detect any impairment.[6] For whole orchestras, experiment has shown that the elimination of frequencies below 40 and above 15,000 cycles per second is undetectable.[4] If the upper limit of the transmitted frequencies is lowered from 15,000 cycles, the impairment is at first barely detectable but increases at an accelerating rate. When the limit is materially lower than 8,000 cycles, the loss is readily apparent to many people.

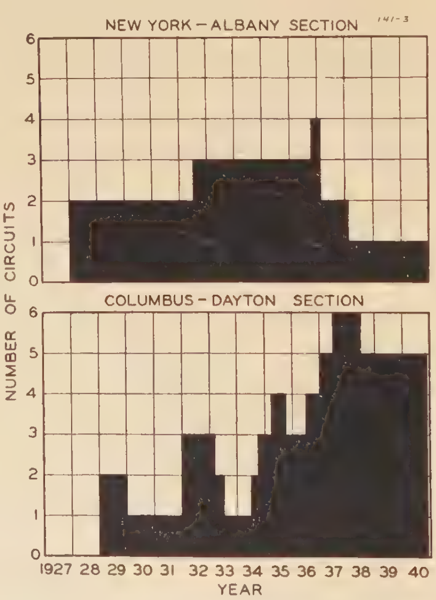


Figure 3. Variations in full-time program circuits

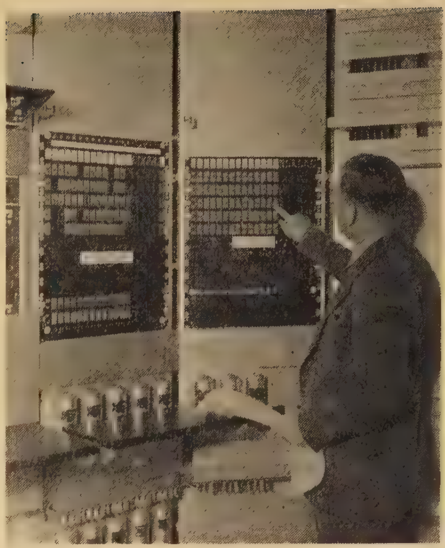


Figure 4. Switching panel at Omaha, Nebraska

Another important consideration is volume range—that is the difference between the maximum and minimum levels of the program. The ordinates of figure 6 show that for part of the frequency range, the ear can respond to a range of intensities of more than 120 decibels, with perhaps 100 decibels as a mean. However, the following considerations show that the volume range which the transmission system needs to accommodate is considerably narrower than the intensity range to which the ear can respond.

In the first place, the range of program volumes to which the ear can respond is much less than the range of single-frequency intensities shown by the curve. Program waves are in general very irregular in shape, and even at constant volume contain large and small peaks differing in amplitude by many decibels. The range between the volume at which the highest peaks reach the maximum instantaneous intensity which the ear can tolerate and the volume at which the smallest peaks are just above the threshold of audibility is therefore less by a number of decibels than the intensity range of the ear as measured by single frequencies.

In the second place, the volume range of the usual program material has definite limits. Measurements have shown that a large symphony orchestra produces a maximum volume range of about 70 decibels.[4] The volume range of most other types of program is considerably less than this, for example, being only about 25 to 30 decibles for dance music and as little as about 15 decibels for much of the dialogue of actors in radio drama.

In the third place, the usual listening

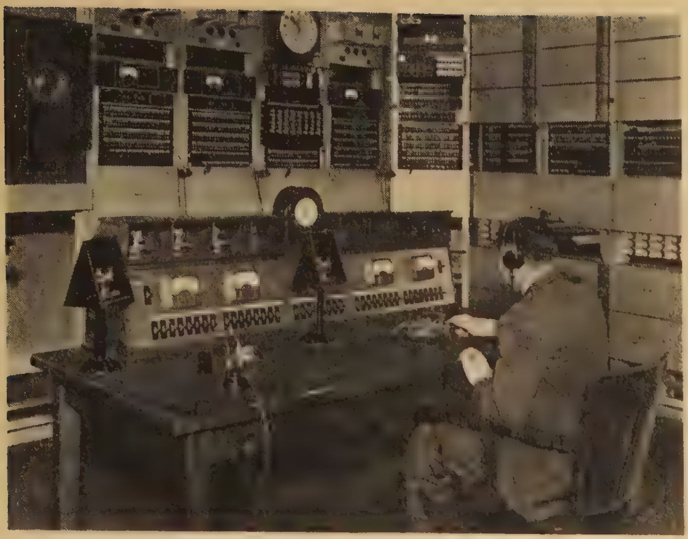


Figure 5. Monitoring position at Washington, D. C.

conditions impose a definite limit on the useful volume range. The loudest passages in the music of a symphony orchestra correspond to a sound level of about +95 decibels at a point, say one-third the way back in an auditorium, but most people in their homes prefer a level which is lower than this by 5 to 10 decibels. Figure 8 shows the results of an extensive survey[7] of acoustic room noise in homes. It will be noted that the average noise level is +43 decibels on the sound-level scale, and that few homes are quieter than +30 decibels even in the suburbs. The signal-to-noise range inherent in the listening conditions, and allowing nothing for the noise contributed by the transmission system or the room noise where the program is being produced, is therefore seen to be somewhere between 45 and 65 decibels. There is therefore, no advantage to the listener in providing a permissible volume range materially wider than this in the transmission system.

The above discussion applies primarily to the transmission of symphonic and similar high-grade program material. Much program material is less exacting in its requirements, but on the other hand some sound effects such as the tearing of paper require the reproduction of higher frequencies for complete naturalness.

With these broad considerations in mind, the requirements of high-quality program circuits may now be taken up. As has been noted, the program network is but one part of the over-all broadcasting system which, in addition, includes microphones and studio equipment, radio transmitters, and the home receivers with their loud-speakers. It may be taken as a goal for the program networks that their transmission be nearly enough distortionless so that the over-all performance in regard to naturalness of reproduction will not be limited by them.

To meet such a requirement for short program circuits having only one or two sections is not difficult technically, and does not in general require costly types of plant. However, the vast country-wide program networks are made up of many sections of circuits in tandem, which as mentioned before may total in some cases as much as 7,000 miles. This makes it necessary to design and operate the individual circuits to very close limits so that the cumulative discrepancies in the whole network will not exceed tolerable values; and to consider carefully the types of plant employed lest by virtue of sheer numbers of units involved, the total cost be out of line with the over-all grade of service being given the listener. These two conflicting factors are important ones in the consideration of transmission requirements for networks. The determination of the practical working characteristics of program networks involves a consideration not only of the physical and cost factors discussed above but also of such other factors as cost of studios, broadcast transmitters and receivers, and the limitations of the frequency allocations of broadcast stations.

From the standpoint of frequency band the consideration of all factors has resulted in the major present-day program networks being set up to transmit a frequency band with an upper limit of about 5,000 cycles. All program facilities installed in the last ten years or so, however, have been designed to be adaptable to the future transmission of frequencies up to 8,000 cycles. Operation on an 8,000-cycle basis, however, requires the release of additional frequency space now occupied by other services in much of the plant and a general readjustment of the program-circuit characteristics. In 1933, experimental wire circuits were set up between Philadelphia and Washington to transmit frequency bands up to 15,000 cycles. These were employed in a demonstration of stereophonic transmission and reproduction of music.[4] Studio-transmitter loops have been provided to transmit wider frequency bands than the 5,000 cycles currently provided on the nation-wide networks. At the present time, many of the studio-transmitter loops are being set up to transmit bands up to 15,000 cycles. A demonstration will be given at the close of the paper of the transmission of programs over cable circuits about 1,200 miles in length with frequency bands extending to 15,000, 8,000, and 5,000 cycles. The 5,000-cycle circuit is of the type in present commercial use. The 8,000-cycle circuit is of a type to which much of the present program plant can readily be modified. The 15,000-cycle circuit consists of a standard carrier system to which has been added program terminal equipment now under development.

In the consideration of transmission requirements for program circuits other than nominal frequency band, the varia-

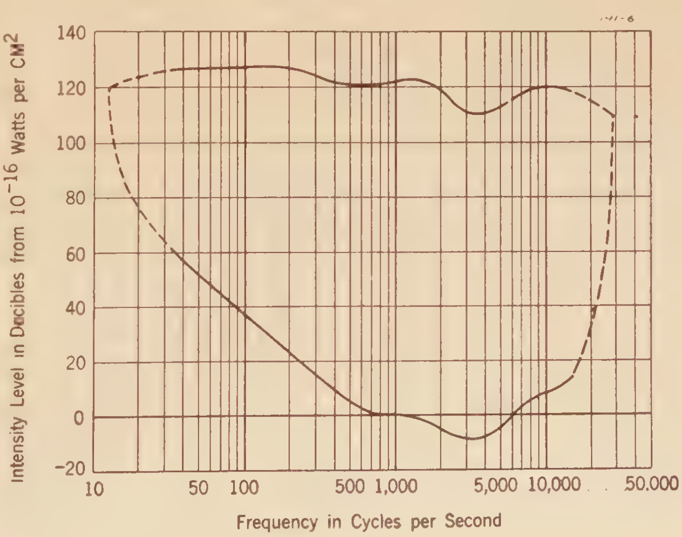


Figure 6. Limits of audible sound

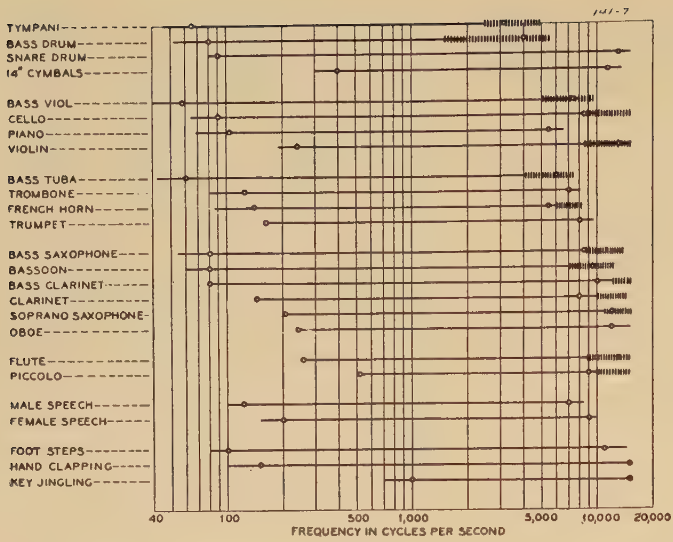


Figure 7. Audible frequency ranges of music, speech, and noise

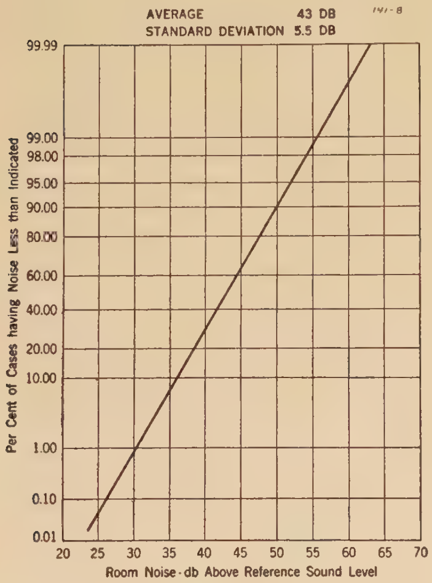


Figure 8. Residence room noise with radio sets silent

tion in performance with length and type of circuit is important, since the factors tending to impair transmission are in the nature of small amounts of distortion or noise which accumulate over the length of the circuit. If these effects varied in some definite manner with length, transmission requirements could be fixed on that basis. However, good engineering practice frequently requires choosing for the various sections of a long circuit, different types of facilities whose contributions to the total effects are not in proportion to their length. Even the determination of the maximum permissible distortion and noise on a circuit is influenced by outside factors such as are involved in the broadcasters weighing operating flexibility and cost against the frequency of occurrence of unfavorable network routings and the number of stations affected. For example, in order to secure operating flexibility with a minimum of total network mileage, most of the networks employ the so-called "round robin" principle for a part of the network. In this arrangement the circuit follows a route from station to station forming a continuous loop which returns to its starting point. This naturally results in increased circuit mileage between the program source and the more distant listeners with an attendant increase in undesired transmission effects. For these reasons no exact or specific transmission requirements can be stated for even the over-all performance of program transmission service.

Volume Range

The permissible volume range for a program circuit is determined by the maximum volume which can be transmitted as limited by nonlinear distortion or cross talk, and the minimum volume which can be transmitted without impairment from the noise present on the circuit.

In connection with their design the various types of program circuit are subjected to listening tests in which the transmission of program over a long loop of the circuit is compared with transmission over a local distortionless circuit. Each type of circuit thus is rated as to the maximum volume it can transmit without noticeable distortion. The highest volume which can be permitted without excessive cross talk into other program or message telephone circuits is also investigated, and whichever limit is the lower determines the maximum allowable working volume for service. The range between the maximum permissible volume and the noise level on very long lengths of the present program circuits is about 45 or 50 decibels, except under some conditions on certain open-wire sections. On the individual links making up the long circuit, the range is 10 or 20 decibels greater than this.

Attenuation and Delay Distortion

Another important consideration is the amount of attenuation and delay (or phase) distortion to be permitted within the transmitted frequency band. It is the practice to equip program circuits with adjustable attentuation equalizers. By means of these once the desired frequency band has been chosen the deviation in attenuation at any frequency within that band, compared with that at 1,000 cycles, can be adjusted within close limits. On very long circuits, however, experience has shown that even with automatic regulating features and careful operation residual variations which may amount to several decibels may develop as a result of changing temperature and other conditions. These variations are kept within tolerable limits by readjustment of the equalizers from time to time.

Associated with the attenuation distortion is another effect detrimental to program quality, namely, differences in time of transmission for different frequency components of the signal. In practice circuits tend to have a lower velocity of transmission near the edges of the frequency band than in the middle portions. This results in frequency components near the edges being delayed as compared to the middle portions of the band. This difference in time of transmission is called delay distortion of the circuit. Careful listening tests have shown that it becomes noticeable if, at the highest transmitted frequency, the delay is more than eight milliseconds greater than at 1,000 cycles, and if, at 100 cycles, it is more than about 15 milliseconds greater than at 1,000 cycles. It is controlled by careful attention to the design of loading systems, amplifiers, repeating coils, and all other elements of the circuit. Since such small amounts of over-all delay distortion are detectable and since networks frequently have 100 or more amplifiers in tandem between an originating point and the broadcasting stations on the more distant portions of the networks, it is necessary that the delay distortion of all individual components of a network be held to exceedingly close limits. Accumulations of residual delay distortion which cannot be entirely eliminated in design are reduced by the use of delay equalizers along the circuits when they are set up.

Conclusion

From this discussion it is seen that the program networks are comprised of many parts, each of which must meet exacting requirements in order that over-all results will be satisfactory. It is seen that equally important with transmission are the requirements for plant flexibility, adequate reserves, uniform practices, and centralized supervision of the networks.

The features discussed have been those found desirable for present-day network service. As indicated earlier, consideration of the needs of the future as well as those of the present is an essential feature of the design and engineering of the plant for program-network service. As a result of having done this it will be possible to provide with present plant, and with new plant currently being installed, adequate network facilities as the broadcasting art develops toward higher standards of performance. With the past experience as a guide, it appears that there should be no fundamental difficulty in meeting all reasonable requirements, always remembering that in the long run, requirements and costs bear definite relations to each other.

References

1. Telephone Circuits for Program Transmission, F. A. Cowan. AIEE Transactions, volume 48, number 3, July 1929, pages 1045–9.

2. Long Distance Cable Circuit for Program Transmission, A. B. Clark and C. W. Green. *Bell System Technical Journal*, volume 9, number 3, July 1930, pages 567–94.

3. Wide Band Open Wire Program System, H. S. Hamilton. Electrical Engineering, volume 53, number 4, April 1934, pages 550–62.

4. Symposium on Wire Transmission of Symphonic Music and Its Reproduction in Auditory Perspective, Electrical Engineering, volume 53, number 1, January 1934, pages 9–32, 214–19:

Basic Requirements, Harvey Fletcher.

Physical Factors, J. C. Steinberg and W. B. Snow.

Loud Speakers and Microphones, E. C. Wente and A. L. Thuras.

Amplifiers, E. O. Scriven.

Transmission Lines, H. A. Affel, R. W. Chesnut, and R. N. Mills.

System Adaptation, E. H. Bedell and Iden Kerney.

5. Absolute Amplitude and Spectra of Certain Musical Instruments and Orchestras, L. J. Sivian, H. K. Dunn, and S. D. White. *Journal Acoustical Society of America*, volume II, January 1931, pages 330–71.

6. Audible Frequency Range of Music, Speech and Noise, W. B. Snow. *Journal Acoustical Society of America*, volume III, July 1934, pages 155–6.

7. Two papers: Room Noise at Telephone Locations, D. F. Seacord. Electrical Engineering, volume 58, number 6, June 1939, pages 255–7, and volume 59, number 6, June 1940, pages 232–4.

Prime-Mover Speed Governors for Interconnected Systems

R. J. CAUGHEY
NONMEMBER AIEE

J. B. McCLURE
ASSOCIATE AIEE

Synopsis: System operating requirements, from the standpoint of frequency and tie-line loading, are continually becoming more rigorous and receiving more widespread attention. Supplementary controls have been developed to assist in the solution of these problems—but the speed governors of the prime movers still constitute the backbone of system control.

This paper outlines the general problems encountered; gives definitions of terms for both steam and hydro governors and discusses the performance characteristics of these two general classes of prime movers. As a result of discussions with several operating groups certain definite conclusions were reached for prime-mover governor characteristics on the larger systems, viz., dead band should be as small as practicable; uniform incremental regulation desirable; adjustable regulation not necessary; similar rates of response not necessary and accurate response to supplementary control desirable. These conclusions are supported by the analytical work presented in the companion paper.[7]

A summary of the reasoning supporting these conclusions under the subjects of stability, dead band, regulation, response, short circuits, and tie-line swings is included.

Paper 41-24, recommended by the AIEE committee on power generation, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 27, 1940; made available for preprinting December 3, 1940.

R. J. Caughey and J. B. McClure are with the General Electric Company, Schenectady, N. Y., Mr. Caughey in the turbine engineering department and Mr. McClure in the central station engineering department. J. B. McClure and R. J. Caughey are members of The American Society of Mechanical Engineers.

The authors wish to express appreciation to the representatives of the operating companies who contributed during the several discussions on this subject and to acknowledge the assistance of Messrs. C. Concordia, S. B. Crary, and E. E. Parker of the General Electric Company in the preparation of this paper.

1. For all numbered references, see list at end of paper.

Introduction

During the past several years the interconnected power system has come into being and has expanded rapidly to the point where some of these systems now comprise several million kilovolt-amperes of connected capacity. Many problems have appeared and of these, two important and closely associated ones, speed and load control, have continued to receive increased attention. In most cases large portions of these systems are tied together by tie lines of relatively small capacity and as a result power flow across the ties must be carefully controlled.

Frequency control is being widely used in varying degrees of refinement and automatic tie-line control is being used in more and more locations.[1,12,13,14] The control associated with these two problems is usually applied in the form of relatively slow supplementary adjustments to the normal action of the basic speed governors, which still constitute the backbone of system control. It is logical, then, as system operation becomes more refined and the requirements more rigorous, that more attention[2,3,4] be given to the characteristics of the speed governing mechanisms. During this same period special instruments[8,9,10] for accurately measuring small changes in system frequency have been developed and these instruments have been used to advantage by several groups in analyzing governor performance.

The manufacturers of power generating equipment endeavor to equip their prime movers with suitable governing equipment.[5,6] Also, in the analysis of power system performance it is essential to appreciate the influence of all associated apparatus, including speed governors[11,15] on system performance. On this basis, the general problems associated with speed governing were discussed with several operating groups, and with the evidence procured so far, we have reached certain definite conclusions as to what characteristics prime mover governors should have to meet the operating requirements on the larger power systems.

Definition of Terms

There is a surprising lack of a common language for this subject and thus, before proceeding further a brief definition of terminology used *in this paper* will be in order. Two sections in the ASME—Power Test Codes for Governors and Committee on Industrial Instruments and Regulators—each have a set of definitions and this is no attempt to

arbitrate any differences, or establish new terms. A final decision on terminology will be reached through mutual agreement between representatives of manufacturers and operating groups both in the AIEE and ASME as well as other contributing groups.

Speed governor shall include the speed responsive element which positions a member in terms of speed. In figure 1 this is schematically represented by a conventional spring-restrained centrifugal flyball mechanism, but an oil pump working against a spring loaded diaphragm or a resonant circuit producing a torque motor effect will perform the same function.

Control mechanism shall include all linkages, pilot valves, dashpots, operating cylinders, cam shaft, cams and valves necessary to control the prime mover input in terms of speed governor position. In figure 1 a single pilot valve is shown between the speed governor and the operating cylinder. As the required pilot-valve size increases, a larger and more powerful speed governor is required. Instead of this, a relay mechanism or amplifier consisting of an intermediate pilot valve and piston is often interposed between the speed governor and the main pilot valve.

Governing mechanism shall include both the speed governor and control mechanism all as shown schematically in figure 1.

Over-all regulation is the sustained per cent change in speed of a prime mover for full load change from an initial speed of 100 per cent.

The regulation of the mechanism shown in figure 1 may be changed by varying the ratio of linkages, but there is always a lower limit for regulation below which stable operation cannot be obtained. This limit is determined by system conditions as well as by governor mechanism characteristics—but other conditions being similar, faster mechanisms permit smaller regulation with stability.*

Operating piston times for steam units are in the order of one second or less—whereas servo-motor times in hydro units are four seconds or greater to satisfy hydraulic conditions. Thus, if this simple mechanism in figure 1 were employed in a hydro governor, the regulation required for stability would be so large that other operating requirements would not be satisfied.

The manufacturers of hydro governors have solved this problem very neatly by employing droop correction as shown in figure 2. For sudden changes the dashpot

*Figure 3, reference 7.

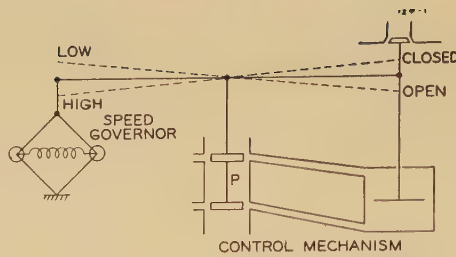


Figure 1. Schematic diagram of speed governing mechanism

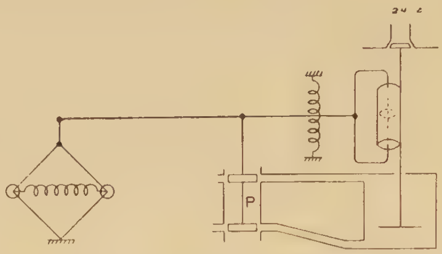


Figure 2. Schematic diagram of speed governing mechanism with compensating dashpot for droop correction, arranged for zero droop

acts as a rigid connection—giving broad transient regulation for stability, but after some time delay, the action of the dashpot and springs produces a much smaller steady-state regulation. In the figure, zero steady-state regulation is shown, but for paralleling purposes, the necessary amount of over-all steady-state regulation is obtained by positioning the spring supports in terms of operating cylinder position. Thus, droop (the remaining droop after the correction has operated) and over-all regulation are synonymous.

Incremental regulation is the slope of the speed-kilowatt curve passing through 100 per cent speed at the load in question, expressed in per cent of rated speed.

Unfortunately the uniform characteristic shown in figure 4 is not so easy to obtain and requires proper co-ordination in the design of both the speed-position characteristic of the governor and the flow-travel curve of the control mechanism. In the case of a hydro unit, the increase in flow for increased gate openings tends to fall off at the larger gate openings. In this respect most steam turbines have several inlet valves, each having its flow-travel characteristic. A comparison is shown in figure 3 where the dotted curve applies to a hydro unit and the solid curve to a four-valve steam unit.

Mechanisms as in figure 2 have both transient and steady-state incremental regulation. As far as governor influence is concerned, load division between units on a system is determined initially by transient incremental regulation and subsequently by the steady-state incremental regulation. Since most load changes on the larger systems are relatively slow, steady-state incremental regulation is the significant characteristic.

Dead band is the magnitude of the sustained speed change within which change of prime mover input will not be produced. Figure 4 shows two governors with equal dead band, one having broad and the other narrow over-all regulation. It may be seen that the governor having broader regulation will hold its load within a smaller range for a constant frequency and for the same frequency dead band, than the governor with narrow regulation. This dead band is a measure of the sensitivity of the mechanism. A method of simultaneously recording speed on one axis and mechanism movement on the other axis has been developed using apparatus similar to that described in reference 8. When proper interpretation of such records can be made, this method should prove useful in determining the over-all dead band of governing mechanisms while in service.

Supplementary adjustment—Any means employed to adjust externally the prime mover input.

Conclusions

The following conclusions, which apply to the requirements of both steam and hydro units, have been arrived at after having considered operating requirements, nature of load changes on large systems, reliability of operation, simplicity in mechanisms, and ease of maintenance.

1. Dead band should be as small as practicable.
2. Uniform incremental regulation is desirable but not essential.
3. Adjustable regulation is not necessary.
4. Similarity of rates of response is not necessary.
5. Accurate response for supplementary adjustment is desirable.
6. Indications of all adjustments are desirable.

A brief review of the reasons supporting the above conclusions follows:

Stability

One of the first and axiomatic requirements is that the mechanism be stable** at all times. A stable governor is one which does not by itself produce or excite an oscillation. A governor with a high degree of, or with good stability, is effective in quickly reducing the magnitude of an oscillation produced by any disturb-

**Figures 1–12 inclusive, reference 7.

ance. Small dead band, broad incremental regulation, both transient and steady-state, and small time lags all contribute to stability and are largely under the control of the designer. Generally, if the unit is stable for synchronizing, it will be still more stable when connected to a system due to the synchronizing and damping torque action provided by the system. For the same reason a governing mechanism which is poor when operated alone may give no trouble when it becomes part of a system already equipped with good governors.*

At the same time a single machine or a number of machines behaving as a group is influenced to a large extent by the damping characteristic of the load, i.e., the change of load per unit of speed change, other conditions being constant.**

Dead Band

Small dead band (small over-all insensitivity) contributes to stability, maintains accurate loads at fixed frequency and gives accurate response to frequency variations. (See figure 4.) Study of this characteristic has convinced us that it is the over-all dead band, rather than dead band of some particular portion of the mechanism, that is the significant factor.†

In a few instances there has been evidence to show that if insensitive governors control the major portion of the system, speed variations may be aggravated by either unnecessary movement of the mechanisms or by insufficient movement caused by the dead band allowing a greater change in frequency before the proper input correction is obtained. These conditions can be overcome by improved design in available mechanisms.

Present evidence indicates that over-all dead band should be made as small as possible just so long as the effort is not carried to the point of requiring undue expense in manufacture, and of requiring undue maintenance in the field to keep that degree of performance. Operating groups can, by tests and analyses, assist the governor designers in establishing the proper economic limit.

Incremental Regulation

The incremental regulation in the normal operating range should be as uniform as is consistent with economical design of the mechanism and efficient turbine operation. By making the incremental regulation as uniform as possible and as large as necessary, stability

*Figure 11, reference 7.

**Figures 3 and 4, reference 7.

†Table 1, reference 7.

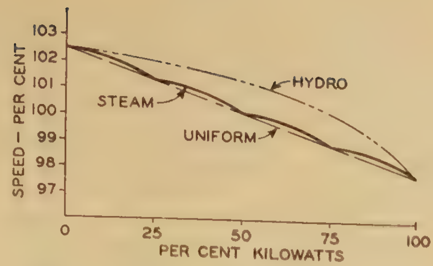


Figure 3. Typical speed-load characteristics for steam and hydro units. Slope of curves at any point is incremental regulation

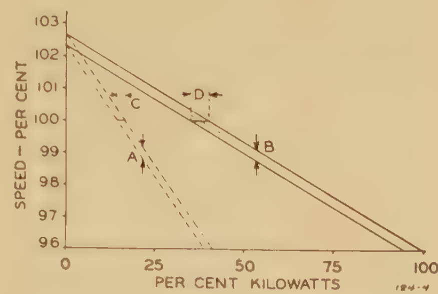


Figure 4. Speed-load curves showing dead band. A and B—Possible speed variation within dead band. C and D—Possible load variation within dead band

margin at all valve points is assured and more uniform response to supplementary adjustment is obtained. If the improved uniformity is obtained entirely through mechanism design, more powerful operating cylinders may be necessary or more complicated mechanisms may be required. If the improved uniformity is obtained by increased overlapping in the valve openings, the turbine efficiency is reduced at the valve openings.

Incremental regulation should be as broad as is consistent with reasonable system speed variations. Broad regulation improves stability, contributes to most rapid settling down after a disturbance, and minimizes any tendency for hunting which might be caused by dead band.

Regulation

For steam turbines the maximum over-all regulation which can be tolerated and still meet the present overspeed and emergency trip requirements is about six per cent, and the minimum over-all regulation for stability is in the order of two or three per cent without droop correction. For this reason it is believed that some reasonable over-all regulation in this range can be used for most steam turbine mechanisms, thus avoiding the added complication of adjustable regulation. An advantage in operating on small over-all regulation might be to reduce slightly the duty on the supplementary corrective devices now employed, but it appears as though there is a good chance of creating a wider frequency fringe by attempting to operate the units of an entire system on small over-all regulation, because of the reduced degree of stability obtained.‡

As previously mentioned, hydro governors ordinarily use a large transient regulation in order to obtain stability and droop correction to obtain reasonably small steady-state regulation. Adjustment of this droop is readily obtained. Where adjustable regulation for steam turbines is considered desirable, it may be provided in two ways; first, with a simple mechanism similar to figure 1 where the linkages are adjustable over the two to six per cent range; second, by adding speed droop correction, figure 2, which permits over-all regulations as low as zero, on one machine.

For smaller systems the per cent load changes relative to system capacity are usually larger and maintaining speed is more of a problem. In these cases governing mechanisms which can, if desired, be operated at zero steady-state regulation have a distinct field of usefulness. It is believed, however, that while mechanisms are being built to meet these special conditions on smaller systems, the conditions on the larger systems do not demand such flexibility in speed governing mechanisms.

Rate of Response

The present rates of response of steam and hydro governors are widely different, and this results in a corresponding redistribution of power flow subsequent to load changes. Usually, the sudden load changes on most large systems are relatively small and the major load changes occur at a rate which can be followed by even the slowest mechanisms. In an interconnected system, all active governors respond to all load changes regardless of location in proportion to their ability, and in principle it is the function of supplementary control (manual or automatic, or both) finally to allocate a load change in any area to generation in the same area. Any redistribution of load due to different governor characteristics is so masked by real load changes that it is not considered important to modify designs in order to match characteristics.

Matching characteristics of steam and hydro units would mean slowing down steam turbine governor response to approach that dictated by hydraulic limitations on hydro units, whereas actually in

‡Figures 3 and 14, reference 7.

the interest of limiting overspeeds and improving stability it appears desirable to make steam governor response as rapid as is possible without complicating the mechanism. However, in this regard there is no necessity of attempting to make governors which are responsive to rate of change of speed, e.g., inertia governors, since overspeed and stability requirements can both be adequately met with a pure speed responsive mechanism.

Terminal frequency has been suggested to provide speed indication for the governor. This method has no advantages so far as performance is concerned over using shaft speed, but it does have at least two distinct disadvantages, both based on the probability that during out-of-step conditions, it may not indicate the actual speed of the unit. As a result, first, in the case of a turbine generator, a separate pre-emergency device to prevent tripping the emergency on overspeed would be required; second, the unit is not intelligently helped to pull back into step. The use of terminal drive has been generally limited to small hydro machines in locations where these disadvantages are not important.

System Short Circuits

In transient stability calculations of systems (studies of the ability of generators to remain in synchronism after a disturbance), governor performance is usually neglected and this assumption gives only slightly pessimistic results for the amount of power which can be transmitted through a short-circuit disturbance.

Fast switching is being commonly used and with breaker speeds now commercially available, stability during short circuits at practical loadings for transmission lines is possible, so that very little gain can be expected through improved governor performance during this short interval. The governing mechanism will do its share if it assists in damping out the subsequent synchronous oscillation.

Out-of-Step Conditions

Out-of-step operation has occurred usually as a result of too slow clearing of a severe fault. When the fault is finally cleared, the generator or station is running faster than the rest of the system. If hydro units are involved, large overspeeds may occur, and system relays will probably trip on overcurrents before the units will resynchronize themselves, even if supplementary means are employed.

Steam units, on the other hand, have faster governing mechanisms, much better induction torque characteristics due to the solid rotor generator construction and a stronger electrical tie to the system and load. Therefore, the units settle down soon at a low overspeed. This situation alone gives a good opportunity for self-resynchronizing. As a supplementary measure, increasing the field strength is probably one of the easiest and best assurances of resynchronizing, although some have advocated reducing the input torque.[16]

Tie-Line Load Swings

The normal tie-line power fluctuations due to sudden load changes cannot be appreciably reduced by governor operation, regardless of rate of response, since the initial power flow is largely determined by the system and tie-line impedances, later modified by inertias and finally determined by governor action. Gradual load changes will be divided according to composite governor characteristics of various portions of the system and later modified by supplementary control.

In the steady-state condition most tie lines have a sustained power oscillation at the natural frequency of the interconnected groups. These power oscillations are usually a small percentage of the tie-line capacities and alone represent no problem. With these power oscillations there is associated a speed oscillation of small magnitude. Experience and our studies[7] indicate that the characteristic of these swings may be influenced by governor action, but usually should be within reasonably satisfactory limits with ordinary governor performance. In those cases where the governors tend to excite unnecessary power oscillations, proper adjustment of the governor characteristics, for example, broadening the regulation, should eliminate the tendency.

Adjustment and Indications

Supplementary adjustment is provided on all speed governors and may be used for either manual or automatic correction. This adjustment should be arranged so that reasonably uniform response is assured throughout the operating range.

Gate position indication has been available on hydro units for some time and indication of operating piston position on steam units, with valve opening points marked, has been suggested. Gate indication on a hydro unit is often more useful than a wattmeter, particularly on a variable head installation and on a steam unit it is desirable to avoid operation at partial valve openings. With the more recent turbines a recorder is being provided which records speed of the unit prior to synchronizing and which records cam shaft position after synchronizing. This arrangement gives a complete record of the manner in which the machine has been brought up to speed and loaded.

Load-limiting features are furnished on most turbines and are still being used to some extent. This feature is particularly useful in maintaining a fixed load on a machine connected to a system where the frequency is allowed to vary through wide limits. On most large systems, today, frequency is normally held within a 0.1-cycle band by means of supplementary control. Any machine equipped with a five per cent speed governor will change load by only three per cent in response to such a frequency change and most steam operators agree that this is essentially fixed load, for machines carrying a reasonable load. In general, the frequency fringe on a system is reduced by increasing the percentage of machines on governor control, and to this end load limit as such may be advantageously discarded except as a back-up measure to prevent severe overloads on boilers and associated equipment during system emergencies.

Summary

The conclusions which have already been enumerated and discussed apply to governing mechanisms of prime movers on the larger systems. For smaller systems governing mechanisms which can, if desired, be operated at zero steady-state regulation, have a distinct field of usefulness. For governing mechanisms on the large systems, emphasis should be placed on obtaining uniform incremental regulation, accurate response for supplementary control, and small dead band. The experience and judgment of the operating groups will be of assistance in determining the economic limit, beyond which the design cannot be justifiably carried.

Bibliography

1. Frequency, Time, and Tie-Line Load Control on Interconnected Systems, **Philip Sporn** and **V. M. Marquis**. *Electrical World*, March 12, 1932, page 495 and April 2, 1932, page 618.

2. Experiences in System Speed Regulation, **Otto Holden**. ASME *Transactions*, volume 62, April 1940, number 3, page 237.

3. The Field of System Governing, **Albion Davis**. ASME *Transactions*, volume 62, April 1940, number 3, page 207.

4. Regulation of System Load and Frequency, **Herbert Estrada** and **H. A. Dryer**. ASME *Transactions*, volume 62, April 1940, number 3, page 221.

5. Constant System Speed and the Steam-Turbine Governor, **A. F. Schwendner**. ASME *Transactions*, volume 62, April 1940, number 3, page 199.

6. Steam-Turbine Governors, **R. J. Caughey**. ASME *Transactions*, volume 62, April 1940, number 3, page 191.

7. Effect of Prime-Mover Speed Governor Characteristics on Power-Frequency Variations and Tie-Line Power Swings, **C. Concordia**,

Analysis of Short-Circuit Oscillograms

W. W. KUYPER
ASSOCIATE AIEE

Summary

METHODS of analyzing the oscillograms of short circuit currents of synchronous machines, in accordance with the two reaction theory, are presented in this paper. Differences between the results found here and the more generally accepted equations, based on symmetrical components, are pointed out.

Introduction

The analysis of short circuit oscillograms to obtain synchronous machine reactances is usually made by means of the equations developed from symmetrical component theories. These equations have been employed by previous writers on the subject and have been incorporated in published standards. Because symmetrical component methods usually start from the assumption of sinusoidal currents of single frequency in the armature, and because it is known that short circuit currents depart appreciably from the simple sinusoidal form, it is desirable to know the effect of removing the assumption of sinusoidal currents on the equations used in the analysis of short circuit oscillograms.

The two reaction theory of synchronous machines, as developed by Doherty and Nickle[1,2], permits a calculation of the harmonics of armature current. The method has been widely used to determine operating characteristics of machines; but the application to the calculation of machine quantities from oscillograms of short circuit currents is not well known. It is the purpose of this paper to show how the two reaction theory applies in such a determination of reactances.

The equations of armature current as previously published are restated here. From these equations, expressions for the envelopes of the currents are written. These envelopes have certain slight limitations which will be mentioned later, but, except in rare cases, they may be drawn readily on the oscillogram. The equations of the envelopes permit a simple statement of the relations between the voltages, currents and reactances.

The two reaction theory has been checked by test within the limits of the assumptions under which it was derived. The results herein described have about the same limitations and the same degree of applicability. While it is true that the presence of saturation, resistance and nonsinusoidal windings cause appreciable departures from the case of the ideal machine here treated, knowledge of the characteristics of the ideal machine is basal to an understanding of the effects of these complicating factors.

Three-Phase Short Circuit

Doherty and Nickle[2] give the equation of the armature current after a sudden three phase short circuit at the terminals of the machine. It may be shown that the current in one phase, when the effect of an amortisseur is included, is defined by the following equation.

$$i=\frac{e_0F_3}{x_d''}\cos(t-\alpha)-\frac{e_0(x_d''+x_q'')}{2x_d''x_q''}A_3\cos\alpha+\frac{e_0(x_d''-x_q'')}{2x_d''x_q''}A_3\cos(2t-\alpha)\ \text{times normal peak current} \qquad (1)$$

where

i = per unit current at any time t.

Paper 41-2, recommended by the AIEE committee on electrical machinery and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted May 23, 1938; made available for preprinting October 23, 1940.

W. W. KUYPER is assistant engineer, supercharger engineering department, General Electric Company, West Lynn, Mass.

1. For all numbered references, see list at end of paper.

e_0 = per unit voltage before fault (peak value).

t = per unit time, $t=0$ at time of fault. One per unit time is required for the machine to progress through one electrical radian.

α = electrical angle between centerline of armature and centerline of field at the time of the fault.

x_d = per unit direct axis synchronous reactance.

x_d' = per unit direct axis transient reactance.

x_d'' = per unit direct axis subtransient reactance.

x_q'' = per unit quadrature axis subtransient reactance.

σ_a = decrement factor of the armature.

σ_f' = decrement factor of the field, transient.

σ_f'' = decrement factor of the field, subtransient.

$A_3=\epsilon^{-\sigma_a t}$

$$F_3=x_d''\left[\frac{1}{x_d}+\left(\frac{1}{x_d'}-\frac{1}{x_d}\right)\epsilon^{-\sigma_f't}+\left(\frac{1}{x_d''}-\frac{1}{x_d'}\right)\epsilon^{-\sigma_f''t}\right]$$

Consider the case, $\alpha=0$, which gives a fully offset wave.

Subject to conditions stated later, two equations representing the envelope may be written as follows:

$$\text{Envelope line number } 1=\frac{-F_3-A_3}{x_d''}e_0 \qquad (2)$$

$$\text{Envelope line number } 2=\frac{F_3-A_3}{x_d''}e_0 \qquad (3)$$

It may readily be verified that the slopes and values of equation 2 at $t=\pi+2n\pi$ are identical with the slopes and values of equation 1 at $t=\pi+2n\pi$. Similarly, the slopes and values of equations 3 and 1 are equal at $t=0+2n\pi$. Therefore, unless there is more than one maximum per half cycle, they are the envelopes as usually defined. (This latter condition will be discussed later.)

The difference obtained by subtracting equation 2 from equation 3 gives the width of the envelope,

$$\text{width of envelope}=\frac{2F_3e_0}{x_d''}\ \text{(in terms of normal peak current)} \qquad (4)$$

The d-c component of the current is given by the second term of equation 1. For a fully offset wave,

$$\text{d-c component}=\frac{A_3e_0(x_d''+x_q'')}{2x_d''x_q''} \qquad (5)$$

S. B. Crary, and E. E. Parker. AIEE TRANSACTIONS, volume 60, 1941.

8. OSCILLOGRAPH ANALYZES GOVERNOR PERFORMANCE, J. E. Allen. *Power*, November 1934, page 610.

9. PHOTO-ELECTRIC RECORDER, C. W. LaPierre. AIEE TRANSACTIONS, volume 51, 1932, page 221.

10. APPLICATIONS OF THE PHOTO-ELECTRIC RECORDER, W. L. Carson. *General Electric Review* volume 39, April 1936, number 4, page 189.

11. OVERVOLTAGE ON TRANSMISSION SYSTEMS CAUSED BY DROPPING LOAD, E. J. Burnham. AIEE TRANSACTIONS, volume 51, 1932, page 105.

12. AUTOMATIC FREQUENCY CONTROL, Robert Brandt. *Electrical World*, February 1923.

13. PHASE ANGLE CONTROL OF SYSTEM INTERCONNECTIONS, R. E. Pierce and B. W. Hamilton. AIEE TRANSACTIONS, volume 58, 1939 (March section), pages 83–91.

14. TIE-LINE CONTROL WITH FREQUENCY BIAS, E. L. White. *Electrical West*, volume 80, June 1938, page 132.

15. LOAD DUMP TESTS MADE ON COLFAX TURBINES, T. E. Purcell. *Power*, volume 69, January and June 1929, pages 590 and 627.

16. SYNCHRONIZATION OF MACHINES IN DISTURBANCES OF STABILITY, P. S. Shdanow. Conference Internationale des Grands Reseaux Electriques, volume 1, 1935, page 110.

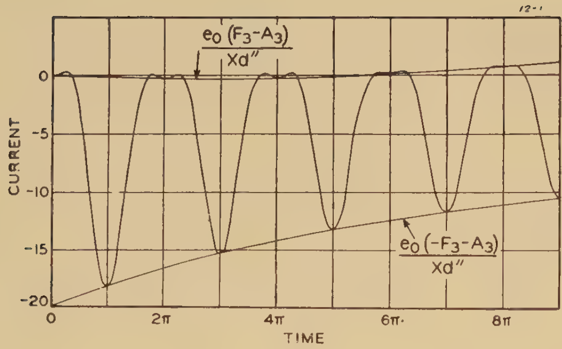


Figure 1. Three-phase fault current and envelope, equations 1, 2, 3

$\alpha=0$
$x_d''=0.10$ per unit
$x_q''/x_d''=3.0$
$x_d'=0.15$ per unit
$x_d=1.00$ per unit
$e_0=1.0$ per unit
$\sigma_a=0.0265$ per unit
$\sigma_f''=0.106$ per unit
$\sigma_f'=0.0076$ per unit

This component is often considered to be traced by the midpoint of the envelope lines. That this is not the case is evidenced by averaging equations 2 and 3, which determines the midpoint:

$$\text{Median line between envelope lines}=\frac{A_3e_0}{x_d''} \tag{6}$$

A study of equation 4, together with the expression given for F directly after equation 1, shows that the envelope width at $t=0$, when extrapolated from the subtransient region, is $2e_0/x_d''$; when extrapolated from the transient region it is $2e_0/x_d'$. These relations have been shown only for the case of $\alpha=0$, giving a fully displaced wave. They also hold at $\alpha=180$, but not for a fault at any other point in the cycle, unless $x_d''=x_q''$.

If the rates of change of the decrement factors, A_3 and F_3, in equation 1 (for $\alpha=0$) are assumed to be zero (in commercial machines they are small compared to the rates of change of the sinusoidal terms) the conditions for maxima and minima of current are:

$$\sin t=0 \tag{7}$$

$$\cos t=\frac{x_q''}{x_q''-x_d''}\,\frac{F_3}{2A_3} \tag{8}$$

The roots of equation 7, substituted into equation 1, with $\alpha=0$, yield the envelope lines, equations 2 and 3. Equation 2 is derived by setting $t=\pi$, 3π, 5π, etc.; equation 3, by setting $t=0$, 2π, 4π, etc. These envelopes have previously been shown to pass through the maximum and minimum points (at 0, 180, 360 deg., etc.) of the current wave, and to have the same rates of change as the current at these points.

Roots of equation 8 exist only when

$$|2A_3(x_q''-x_d'')|>|F_3x_q''| \tag{9}$$

It is apparent that when $x_q''-x_d''$ is small, only one maximum exists per half cycle. Under such conditions the envelope may be drawn on the oscillogram in the usual way and equations 2 and 3 will represent the envelope.

When the inequality (9) is satisfied, equation 8 can be solved and additional maxima are introduced. However, the envelope represented by equations 2 and 3 can still be drawn, and the relations derived from these equations still hold. The manner of constructing the envelope for such conditions is indicated in figure 1.

Calculation of peak currents may be made from the above equations. Consider the first negative peak of figure 1. It is apparent that the maximum current occurs just previous to the point of tangency with the envelope (the 180° point) and that for most purposes this peak value may be approximated by the value at 180°. From equation 1 or 2, this value is

$$\text{peak current}=e_0\,\frac{A_3+F_3}{x_d''}\ \text{times normal peak current} \tag{10}$$

Disregarding the small increase in this value mentioned above, the value of peak current given in equation 10 can be exceeded only if x_d'' is appreciably greater than x_q''. Under this condition the sign of the second harmonic is reversed and the double maximum which is shown in figure 1, near the 360° point, occurs near the 180° point. An examination of figures 1, 2, and 3 shows how the change of sign on the second harmonic component (see equation 1) changes the position of the double maximum. The condition, $x_d''>x_q''$, is uncommon in commercial machines and need not be considered further.

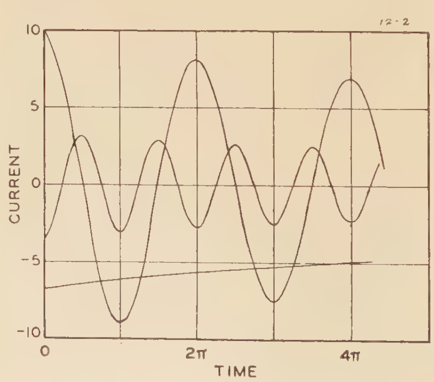


Figure 2. Components of figure 1

The above discussion and equations are valid only for the case $\alpha=0$ (or 180°), which results in a fully offset wave. For a fault at any other point in the cycle, no similar simple relations have been written. However, the extent to which the wave shape changes with change of α is indicated in figure 4. The envelope lines for the case, $x_q''=x_d''$, (where envelope width is $2F_3/x_d''$) are shown to indicate the amount of variation from the simple case which may be expected.

Single-Phase Case

Nickle, Pierce and Henderson[3] give the equation of armature current for single phase short circuit at the machine terminals:

$$i=\frac{3e_0}{k}\,\frac{F_1\cos(t+\alpha)-A_1}{H} \tag{11}$$

or

$$i=\frac{3e_0}{2k}\,\frac{2F_1O}{x_d''+x_2}-\frac{A_1}{x_2}E \tag{12}$$

where

$k\ =1$ for L-N, 3 for L-L fault
$H=(x_d''+x_q'')+(x_d''-x_q'')\cos 2(t+\alpha)$
$A_1=\epsilon^{-at}\cos\alpha$

$$F_1=\frac{x_d''+x_2}{x_d+x_2}+\frac{(x_d''+x_2)(x_d-x_d')}{(x_d+x_2)(x_d'+x_2)}\epsilon^{-\sigma_f't}+\frac{x_d'-x_d''}{x_d'+x_2}\epsilon^{-\sigma_f''t}$$

$O=\ \cos(t+\alpha)+b\cos 3(t+\alpha)+b^2\times\cos 5(t+\alpha)+\ldots$

$E=1+2b\cos 2(t+\alpha)+2b^2\cos 4(t+\alpha)+\ldots$

$$b=\frac{x_2-x_d''}{x_2+x_d''}=\frac{\sqrt{x_q''}-\sqrt{x_d''}}{\sqrt{x_q''}+\sqrt{x_d''}}$$

$x_2=\sqrt{x_d''x_q''}$

For a line-to-neutral fault use $x_d''+\frac{x_0}{2}$ for x_d'' etc.

Similar to the three phase case, the equation of the envelope of the single phase fault current is

$$\text{Envelope line number 1}=\frac{3e_0}{k}\left[\frac{-F_1-A_1}{2x_d''}\right] \tag{13}$$

$$\text{Envelope line number 2}=\left[\frac{3e_0}{k}\,\frac{F_1-A_1}{2x_d''}\right] \tag{14}$$

$$\text{The width of the envelope is }\frac{3e_0}{k}\,\frac{F_1}{x_d''} \tag{15}$$

The extrapolation of the subtransient part of the envelope to $t=0$ yields $\frac{3e_0}{kx_d''}$ times normal peak current. The extrapolation of the transient part of the envelope to $t=0$ yields $\frac{3e_0}{kx_d''}\cdot\frac{(x_d''+x_2)}{(x_d'+x_2)}$.

Similar to the three phase case, unless

$$-1 \leq \left[\frac{A}{F}+\sqrt{\frac{A^2}{F^2}+\frac{x_q''}{x_d''-x_q''}}\right] \leq 1 \text{ and is real} \quad (16)$$

the envelope of equations 13 and 14 is drawn in the usual way. If these conditions do exist, there will be more than one maximum per half cycle, but the envelope lines may still be drawn tangent at the 0° and 180° points, similar to figure 1, which treats the three phase case.

The peak value of the single phase fault current may be written from equation 13. The absolute peak value occurs when the wave is fully offset

$$\text{peak value of current} = \frac{3e_0}{k}\,\frac{F_1+A_1}{2x_d''} \text{ times normal peak value} \quad (17)$$

Certain limitations must be applied to equation 17 similar to those applied to equation 10 which governs the three phase case. Equation 17 can be used with confidence where $x_d''<x_q''$; however, where x_d'' is appreciably greater than x_q'', the absolute peak value of current will occur before the 180° point (assuming a totally offset wave) and may be appreciably greater than the value given by equation 17. This possibility is pointed out but not investigated further because of the improbable nature of the condition.

Conclusions

1. In a single phase line-to-line short circuit the width of the envelope (in terms of normal peak value of current) extrapolated to the time of the fault is $\frac{\sqrt{3}e_0}{x_d''}$. The reactance, x_2, does not appear as it does in the symmetrical component method of analysis, $(2\sqrt{3}e_0)/(x_d''+x_2)$. In a single phase line-to-neutral short circuit the extrapolated value of the envelope width is $3e_0/(x_d''+x_0/2)$.

2. An extrapolation to the time of the fault of the transient part of the envelope of a line-to-line fault shows the width of the envelope to be

$$\frac{\sqrt{3}e_0}{x_d''}\,\frac{x_d''+x_2}{x_d'+x_2}$$

The above relations developed from the two reaction theory indicate that it is not possible to determine x_2 from the subtransient part of the envelope of the current of a line-to-line fault. Any attempt to use the transient part of the envelope to find x_2 is very liable to errors arising from errors in the determination of x_d'' and x_d'.

Similarly, unless x_0 is very large, its accurate determination from the envelope of current of a line-to-neutral fault is not practicable.

3. The peak current on a line-to-line fault is $\sqrt{3}e_0\frac{F_1+A_1}{2x_d''}$ times normal peak current, where A_1 and F_1 are decrement factors, equal to unity at the time of the fault.

The peak current of a line-to-neutral fault is $3e_0\frac{F_1+A_1}{2x_d''+x_0}$.

It is of interest to note that x_2 does not enter in the above expressions as it does in the equations resulting from the use of symmetrical component methods. In every case where $x_2>x_d''$ the symmetrical component equations apparently calculate too low a value of peak current.

4. In an ideal machine, when the armature current in a three phase short circuit is fully offset, the envelope width at the time of the fault is $\frac{2e_0}{x_d''}$ times normal peak current when extrapolated from the subtransient region and $\frac{2e_0}{x_d'}$ when extrapolated from the transient region. In general, this is not true when the fault is made at any position of the rotor other than that which gives a fully offset wave.

In most commercial machines the ratios of machine constants are such that the degree of offset is of little practical importance in the determination of reactance from oscillograms of three phase short circuits. However, in view of the fact that several published statements prefer a symmetrical current wave, the above conclusions preferring a fully offset wave are of interest

The conclusions given here are dependent on a prescribed method of drawing the envelope, which is explained in the body of the paper. In the majority of commercial machines this fact presents no great limitations.

The equations presented above are dependent on the assumption of an ideal machine: negligible resistance; negligible saturation; sinusoidal windings; and a sinusoidal variation of armature subtransient reactance with rotor position. The presence of resistance alters the phase relationship between the current harmonics, although it does not usually cause impedances to be appreciably greater than the associated reactances in short circuits at the machine terminals. Saturation may be partially treated by employing saturated values of the reactances; but the wave form distortion due to the changing values of reactance during the fault and the nonsinusoidal distribution of windings may cause appreciable departures from the calculated wave shape, and thereby vitiate in part the conclusions of this paper. However that may be, a more thorough understanding of the ideal machine relationships should be an aid to more accurate determination of synchronous machine constants from test.

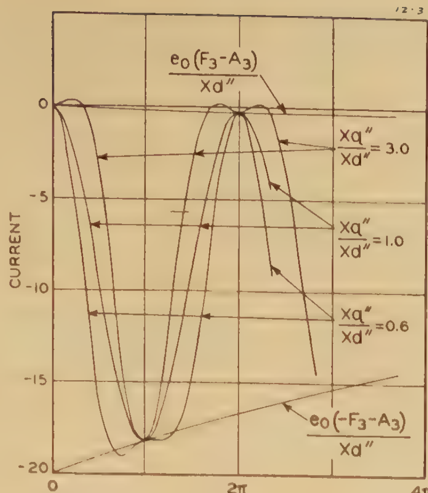


Figure 3. Change of wave shape with change of x_q''/x_d''

Other constants same as in figure 1

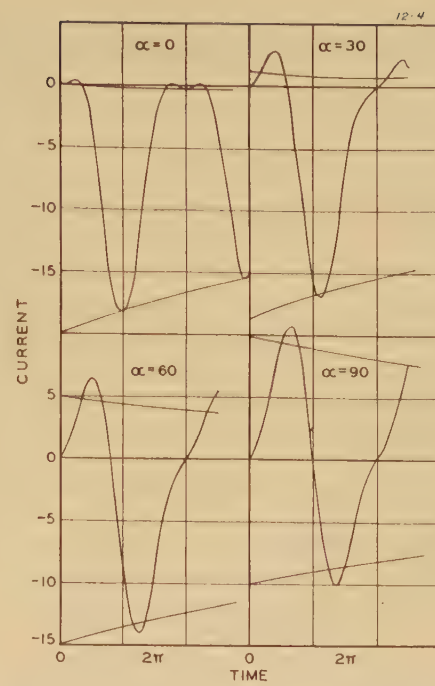


Figure 4. Change of wave shape with change of α

Other constants same as figure 1. See text for description of "envelope" lines

Bibliography

1. Synchronous Machines, Part IV, Doherty and Nickle. AIEE Transactions, volume 47, number 2, 1928, page 514.

2. Synchronous Machines, Part V, Doherty and Nickle. AIEE Transactions, volume 49, number 2, 1930, page 700.

3. Single Phase Short-Circuit Torque of a Synchronous Machine, Nickle, Pierce, and Henderson. AIEE Transactions, volume 51, number 4, 1932, page 966.

Secondary Networks to Serve Industrial Plants

C. A. POWEL
MEMBER AIEE

H. G. BARNETT
ASSOCIATE AIEE

THE design of distribution systems for industrial plants will always constitute individualized problems. There is little hope that any particular form of distribution will be applicable to all industrial plants because the processes of manufacture and the arrangement of buildings differ widely depending on circumstances. There are, however, certain fundamental advantages to the network system of distribution which justify a much wider use than it has found to date. By far the greater part of factory distribution is still of the radial type and the network system must compete with the radial system in economy, reliability, and flexibility. The purpose of this paper is to show that it can do so successfully.

Assuming that the product of the factory is such that a relatively large number of small and medium-sized motors are required rather than a few large ones, it will be found that the physical location in the factory of the various machines is not of such importance in the layout of the distribution scheme as the total connected load, the diversity factor and the over-all power factor, and it is on its ability to take advantage of diversity that some of the economy of the network system rests.

The information available on the load density of factories is quite fragmentary. For the more common products of manufacture it varies from 5 to 30 kw per 1,000 square feet, 10 to 20 being the value mostly encountered, although in exceptional cases it may go as high as 100 kw. Load density should not be confused with the rating of the installed motors and utilization devices. The diversity between the various loads will considerably reduce this figure, and the "demand-factor," that is, the ratio of the maximum demand over a period of time to the sum of the utilization device ratings, which is of significance in determining the transformer capacity to be installed, may be 50 per cent or less.

Paper 41-48, recommended by the AIEE committee on industrial power applications, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 15, 1940; made available for preprinting December 11, 1940.

C. A. Powel and H. G. Barnett are both in the industry engineering department of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

A nominal voltage of 440 volts is widely used in the larger factories using small and medium-sized motors. Some mills have adopted 550 volts which with long radial feeds naturally has an advantage over 440 volts. However, this advantage to a large extent disappears with the network system and 440 volts is preferable. Experience with 208-volt metropolitan networks indicates that motors of 750 horsepower and even larger can readily be started up on a 440-volt network without disturbance.

It is desirable that the 440 volts be maintained at the motor locations without much deviation either up or down, and since the regulation in the network is better than in most existing radial distribution systems, the voltage at the supply source should not be much higher than 440 volts.

In the conventional 208-volt city network, the lighting is carried out at 120 volts with the units connected between the outside conductors and neutral. With 440 volts maintained on the suggested factory network the same possibility exists if 250-volt lighting can be used with safety. The type of lighting that might be operated successfully on 250 volts would include primarily the high-intensity mercury lamps of 250- and 400-watt sizes in high-bay reflectors (figure 1), and for intermediate mounting heights the larger fluorescent lamps.

It is generally found necessary in modern manufacturing methods to change tool machinery and processes around in the factory from time to time to meet market conditions, but it is also true that such changes cannot be of a radical nature as the manufacturing possibilities are limited by the type and size of the building. It is, therefore, advisable in designing the distribution system to make the power available at a number of points conveniently spaced throughout the factory building without too much regard to the detailed location of the individual tools.

The network is well adapted to supplying power to such points, and where the total load is 500 kva or more a network, either a distributed or spot network, will frequently be justified. As the total load increases the network becomes more decisively economical.

It is convenient to divide networks into spot networks and distributed networks. A spot network consists of a bus supplied through two or more network transformers and protectors over two or more primary feeders as shown in figure 2. It may be used in the smaller plants or large commercial buildings where the demand is relatively light and distances short. The distributed network on the other hand comprises a secondary grid, the junction points of which are supplied through network transformers and protectors from two or more primary feeders, as shown in figure 3. There is practically no limit to the load that can be carried on such a grid, and spot networks grow into conventional networks as the load increases.

It is not possible to lay down any definite rules regarding the number of supply points and secondary ties that should be included in factory networks, nor the best

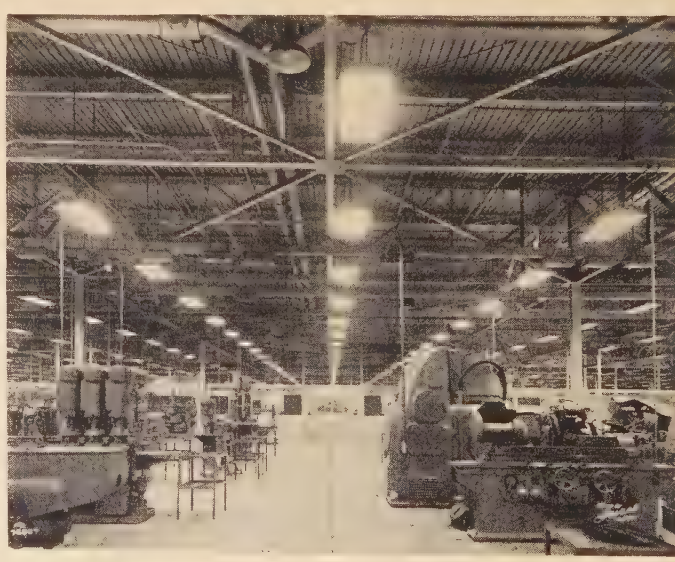


Figure 1. General lighting at an average intensity of 25 foot-candles supplied by three 40-watt daylight fluorescent lamps in each luminaire

size of copper to use. This will depend on the load density and arrangement of the manufacturing aisles in the factory buildings. It can be said, however, that when high current-carrying capacity is required in the secondary mains it is preferable to limit the size of conductor and use two or more smaller conductors in parallel instead of a single large conductor. For example, two 4/0 conductors in parallel provide more carrying capacity than a 500,000-circular-mil conductor and also provide better voltage regulation for a given current at the power factors usually prevailing in distribution systems. Furthermore, in case of a fault in one of these parallel cables, the limiters will isolate it without breaking the network.

The ease with which increasing loads or rearrangement of existing loads in the plant can be taken care of is one of the outstanding advantages of the network system. The addition of a transformer at a junction point of the grid can be made at any time without interruption of service, the relatively small self-contained transformer units with the network protector mounted on it requiring very little space.

Further advantages of the system are reliability, good regulation, and high economy. Reliability is improved by virtue of the fact that the grid is supplied from all the feeders supplying the factory and through all the transformers. The loss of a feeder or transformer would, therefore, pass unnoticed as far as the factory operations are concerned. The regulation is better and the disturbances due to starting up motors are less because of the multiplicity of paths over which the current flows.

In most factories supplied through radial systems of distribution it is usual to put in a substation at some convenient location with one or more transformer banks stepping down the voltage from the power company's primary distribution voltage. A full capacity primary circuit breaker and a 440-volt distribution bus are provided in the substation from which a number of radial feeders are run to the distribution centers in the factory through suitable circuit breakers. The disadvantages of this scheme are obvious.

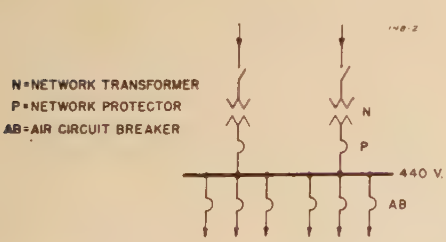


Figure 2. Spot network

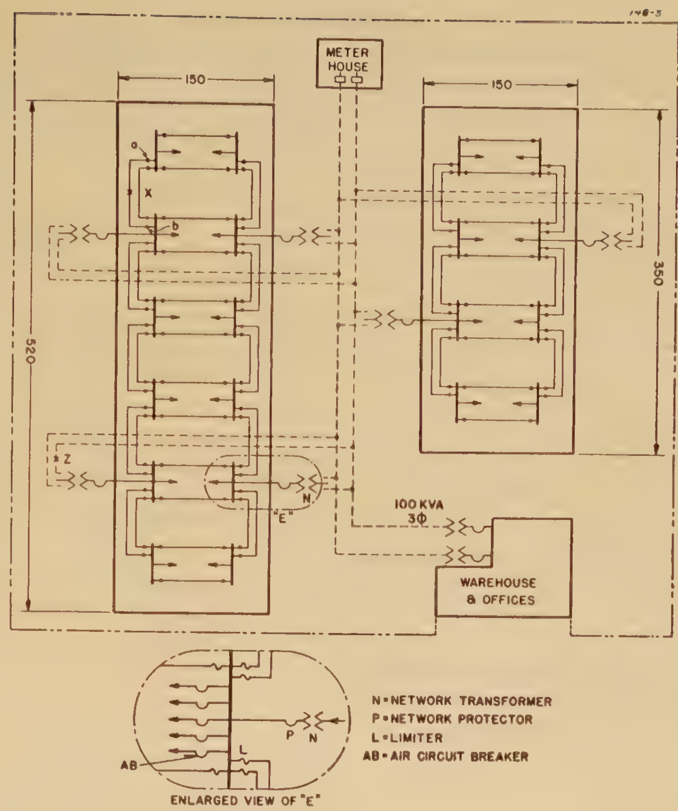


Figure 3. Distributed network for factory buildings

All the breakers must have high rupturing capacity, the low-voltage, that is, the heavy-copper, feeders are of considerable length before reaching the utilization points and maximum economy is obtained only if it is known beforehand exactly what the power requirements are likely to be. Experience has shown that this assumption cannot be made and consequently the transformer capacity installed is usually very much greater than necessary.

A network for a typical factory consisting of two manufacturing and assembly buildings and a five-story office and warehouse building is shown in figure 3. The supply from the utility is over two cables at 13,200 volts, 60 cycles. The maximum demand is 2,500 kva. For taking care of the shop load six transformers of 450 kva, 13,200/440 volts, equipped with primary change-over switches and secondary protectors are provided, and for the warehouse load two 100-kva, 13,200/208-volt, network transformers.

The transformers may be standard oil-filled transformers with network protectors mounted on them, similar to those used in metropolitan distribution systems. In this case they will be placed outside of the factory buildings, either in the open or in vaults. In many cases a more economical installation can be made with air-cooled transformers placed inside the factory buildings, the transformers having mounted at one end an open-type network protector and on the other end a primary switch, the entire unit being enclosed in a single-ventilated housing as shown in figure 4. The network protector of each transformer would be connected to a short bus from which the utilization devices would be supplied through air circuit breakers. These busses would be interconnected among themselves throughout the factory by means of twin cables so as to form the network as indicated in figure 3.

The cardinal principle of the 120/208-volt network system is that secondary faults are burnt clear by the fault current. Experience has shown that while this is entirely desirable and feasible with the low voltages and heavy amperages used in metropolitan distribution, it must be modified for application to factory distribution. At 440 volts secondary faults are not self clearing and it becomes necessary to use protective fuses or limiters at each end of each secondary conductor to definitely clear faults and limit the damage to that section of cable.

With the arrangement proposed it will be seen that an electrical fault anywhere in the plant will leave the major operations undisturbed. The failure of a consuming device will be cleared by its own breaker. A fault on one of the cables forming the network, for instance at *X*, will cause the limiters or fuses *a* and *b* to blow to isolate the fault. These are the only two limiters to carry the full-fault

current and they will, therefore, clear before any other limiter opens. A failure of the transformer or of the primary feeder, for instance at Z, will cause the primary breaker associated with the feeder or transformer to open and also all the network protectors on that feeder. Since the network is designed so that there must be no interruption of service with one primary feeder out of commission, this means that with two feeders the spare transformer capacity would be 100 per cent; with three feeders the spare capacity would be 50 per cent; with four feeders the spare capacity would be 33.3 per cent, and so on. With two feeders the amount of spare capacity is so great as to become uneconomical. Therefore, it is preferable to use a manual throw-over primary switch on each network transformer as indicated in figure 3.

There is a practical limit to the saving in transformer spare capacity by increasing the number of primary feeders, because with increasing number of feeders it becomes impossible to get uniform load division among the transformers left in service when one feeder is out. Also, when more than six feeders are used it is frequently necessary to consider that two feeders may be out of service at once; consequently, seven or eight feeders may require more transformer capacity than four or five feeders. For very large plants this is a very practical consideration and it may dictate the use of two networks in preference to a single network.

The quality of service, that is, reliability and voltage regulation, rendered by the secondary network is better than that provided by any other a-c distribution system. Whether the network is economical in a particular case depends on the degree of reliability required, the amount of flexibility required to meet load growth or change, and the load density and total load to be served.

Whenever it is necessary to provide greater reliability than can be obtained from a simple radial system the network will always be economical, particularly for relatively large loads. To get improved reliability in a radial distribution system it is necessary to use duplicate feeders, manual or automatic throw-over switches or breaker, load-transfer switches, sectionalizing switches or fuses, or other schemes for reducing the duration of outages. For faults on a primary feeder or in a transformer even these special radial schemes do no more than reduce the duration of the outage to a momentary interruption of service, which

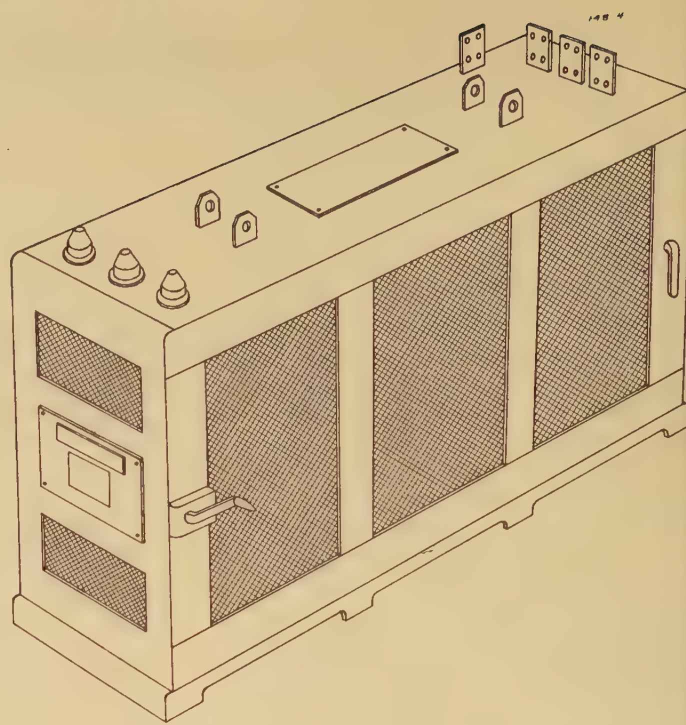


Figure 4. Three-phase indoor air-cooled network unit—transformer, primary switch, and network protector

in many factories may not be permissible. Faults in main secondary circuits will interrupt service to all the load on that circuit until the fault can be repaired. The secondary network eliminates outages due to primary faults and most secondary faults will not interrupt service to any load. The switching equipment required in either manual or automatic radial schemes to provide duplicate power supply is expensive.

The flexibility of the secondary network is an economic advantage. Changes to provide for load growth or changes of load concentration from one part of a plant to another usually can be made by simply installing or moving transformers to meet new load conditions. In the radial scheme any changes in load may necessitate not only changing the transformer capacity but also changing a considerable amount of secondary circuits. Since changes in processes and machines frequently are made in industrial plants, this characteristic of the network system will represent a large saving in many cases.

A comparison of the initial cost of a radial system and of a network system was made for the factory shown in figure 3. In the case of the radial system of distribution a small substation was provided at the upper end of the property comprising a transformer bank of four single-phase units of 833 kva each and primary switchgear consisting of two 500,000-kva, 15-kv oil-circuit breakers with necessary control panels. On the secondary side of the transformer bank a breaker was installed in the leads between the transformer and the 440-volt secondary bus. Five 440-volt radial feeders supply distributing points suitably located in the factory buildings.

In the case of the network system of distribution the primary 13,200-volt cables are brought to the six 440-volt network transformers of 450-kva each. Normally three transformers are connected to one cable and three to the other. In case of a fault on one primary cable the three transformers on the sound cable will be overloaded for the short period of time necessary to operate the primary switches to remove the three transformers from the fault cable and put them onto the sound cable.

With this layout it was found that the network system of distribution showed a saving of approximately 20 per cent over the radial system. It should be noted that in both systems primary circuit breakers were included at the point where the primary cables enter the property. With the network system where a group of primary feeders supply one or more industrial plant networks, it is questionable if these primary breakers are necessary in view of experience with power supply to large commercial buildings from metropolitan secondary networks. The omission of these primary circuit breakers on factory network systems would materially further lower the investment required for the network system as compared to the comparable radial system.

An Electron Microscope for Practical Laboratory Service

V. K. ZWORYKIN
MEMBER AIEE

J. HILLIER
NONMEMBER AIEE

A. W. VANCE
NONMEMBER AIEE

DIRECT observation of extremely minute objects is of great value to both science and industry. Consequently a great deal of time and effort has been spent developing and perfecting optical instruments for making such observations. The modern light microscope is capable of rendering visible detail which is as fine as 0.00002 centimeter. Since the limit of resolving power of the normal eye is between 0.01 and 0.02 centimeter, the maximum useful magnification with these instruments is 1,000 to 2,000 diameters. Where ultraviolet light is used, the useful magnification can be increased to about 3,000 diameters.

The limits discussed above are not due to imperfections in the optical systems or lenses, but are fundamental in nature. It has been shown quite generally that diffraction effects at the object determine the least separation between points or lines on the object which can be resolved. On the basis of this limitation, the resolving power (for lines) at the object is given by

$$d=\frac{0.5\ \lambda}{\mu \sin \alpha}$$

where λ is the wave length of the radiation illuminating the object; μ the index of refraction of the medium in which the object is imbedded, and α the half angle of the cone of light entering the optical system. For visible light the smallest wave length is about 4,000 angstrom units, and the maximum index for the fluid immersing the object is 1.7; therefore, since $\sin \alpha$ cannot be greater than unity, the minimum distinguishable distance is seen to be about 1,200 angstrom units.

From the foregoing it is evident that to extend the range of observation, it is necessary either to find an immersion substance which has a very much greater index of refraction, or to illuminate the object with rays having a much shorter wave length. No known optical medium has an index of refraction greater than two or three, and no liquid suitable for use with an immersion objective has an index greater than the figure used above, namely, 1.7. Therefore, there is little hope of achieving high resolution in this direction. Electromagnetic radiation in the form of X rays and gamma rays has a wave length much shorter than that of visible and ultraviolet light used at present in microscopy. However, due to the fact that lenses or reflectors cannot be made for this portion of the spectrum, advances in this direction are also barred.

For many years the problem of observing appreciably finer detail appeared to be incapable of solution. The search, however, had been restricted almost entirely to the realm of optics, whereas actually the solution lay in an entirely different field—electronics. A little less than 15 years ago it was found that the path of electrons in electric and magnetic fields could be described in terms which are analytically equivalent to those of optics. By means of this electron optical equivalence, it was shown that axially symmetric electric or magnetic fields had the properties of optical lenses, and, consequently, that it is possible to form electron images in the same way that light images can be formed.

At about the same time, the discovery was made that any material particle in motion had associated with it a characteristic wave length. For electrons this wave length, in terms of their velocity expressed in electron volts, is given by the following relation:

$$\lambda=\sqrt{\frac{150}{V}}\ \text{angstrom units}$$

On the basis of this equation, electrons moving with a velocity corresponding to 60 kv have an effective wave length of 0.05 angstrom unit, or only about 1/100,000 that of light. In other words, suitably designed electronic systems employing these high-speed electrons should be capable of extremely high resolving power.

These two concepts led directly and logically to the idea of an electron microscope based on the same principles used in an optical microscope. Such an instrument employs condenser, objective, and projection lenses, performing the same functions as the corresponding elements in the light microscope, but the lenses, instead of being made of glass, are formed by axially symmetric electric or magnetic fields. During the past 10 years, instruments of this type have been investigated in detail in various parts of the world. As a result, the electron microscope has been developed to a point where it is capable of a useful magnification nearly two orders of magnitude greater than the ordinary light microscope. Until recently, the development has been in the hands of physicists, and the instruments built were designed almost entirely for the purpose of studying the microscope itself. However, the microscope has now progressed beyond this stage, and has become a research tool of great potential value.

The problem of realizing this potential value is one for engineers, and as such, its solution was undertaken in the RCA Research Laboratories at Camden, New Jersey. Starting from the basic physical principles, it was necessary to work out the design of an instrument which would be sufficiently simple in operation and rugged in construction to be operated by the average worker in any scientific or industrial research laboratory, and would not require the supervision of a trained physicist. An RCA microscope, developed by L. Marton,[1] which fulfills in part the requirements of a generally practical microscope, was described in an earlier number of ELECTRICAL ENGINEERING.[2] This microscope, although very satisfactory from the standpoint of resolving power, proved to be somewhat difficult to operate and very critical in adjustment and alignment. Furthermore, the instrument and associated equipment occupied a large amount of space.

Work on the electron microscope was continued in order to overcome the objectionable features mentioned above. As a result, an instrument has now been developed by J. Hillier which is completely self-contained, occupies only a small amount of space, and is so simple to adjust and operate that it can be readily handled by any capable laboratory technician.[3] In addition, the microscope incorporates an improved type of magnetic objective lens which increases its resolving power for specimens supported in the manner described below.

Figure 1 is a photograph of the complete microscope. The unit includes not only the microscope itself, but also the regulated power supplies providing the 60-kv over-all voltage and the current for

---

Paper 41-30, recommended by the AIEE committee on communication, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 29, 1940; made available for preprinting December 6, 1940.

V. K. ZWORYKIN, J. HILLIER, and A. W. VANCE are all with the RCA Manufacturing Company, Inc., Camden, N. J. DOCTOR ZWORYKIN is associate director, research laboratories.

1. For all numbered references, see list at end of paper.

130-2

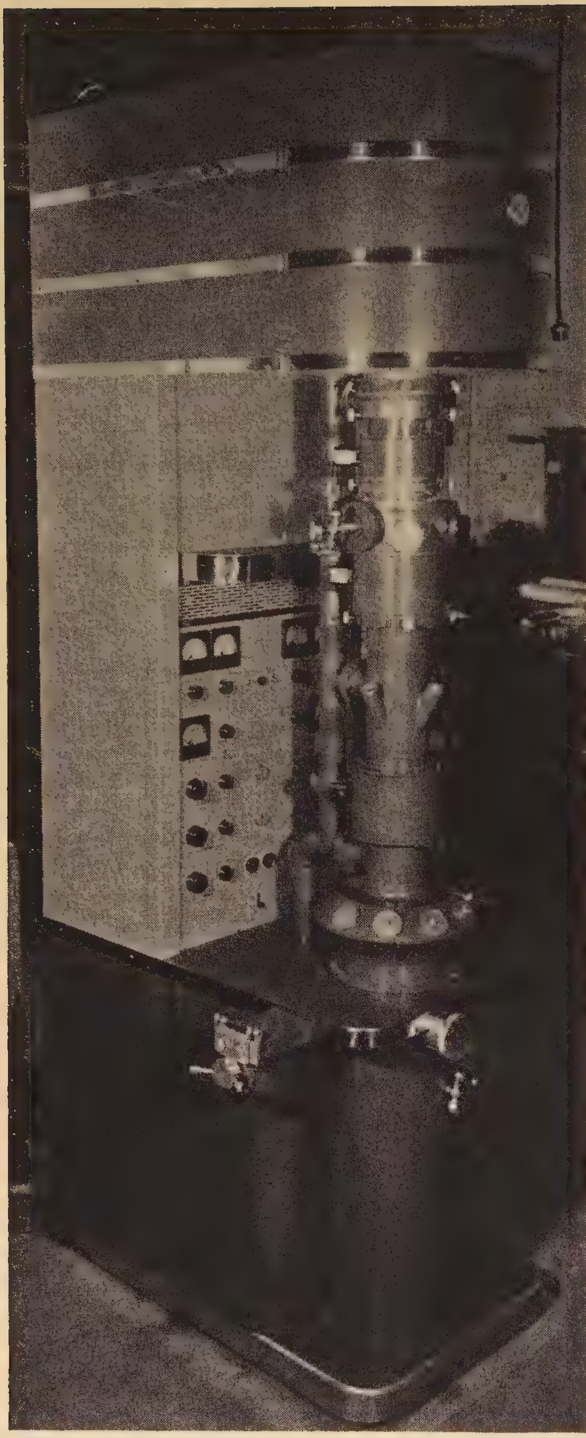


Figure 1. RCA electron microscope

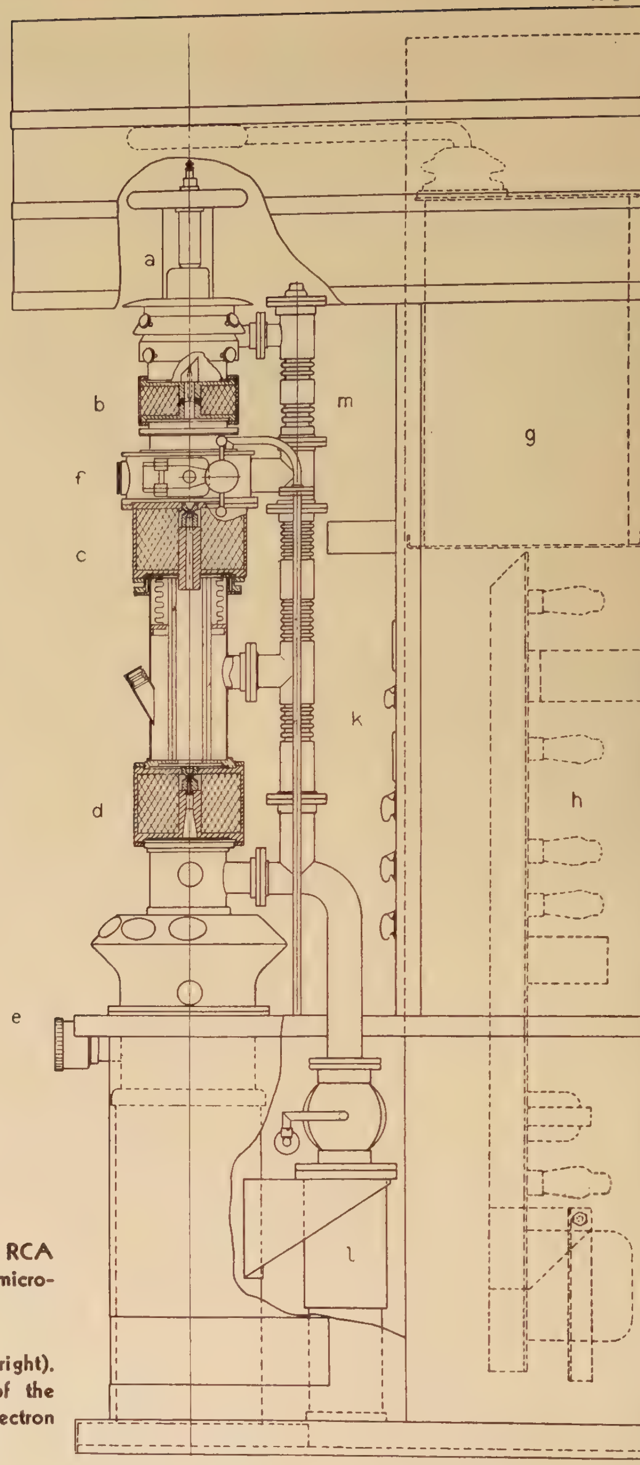


Figure 2 (right). Diagram of the RCA electron microscope

the three magnetic lens coils. The oil diffusion pump for maintaining the required vacuum within the instrument is also contained in the unit.

A simplified drawing is given in figure 2, which shows the construction of the microscope. The electrons used in the imaging process are supplied from the electron gun (*a*), containing a thermionic cathode which is maintained at 60-kv negative with respect to ground, and a final anode at ground potential. Between the two are disposed the electrodes required for governing the electron paths. The electrons leaving the gun have their full velocity, corresponding to 60 kv.

The condenser lens (*b*), which consists of an iron-clad coil with pole pieces shaped to give the required magnetic field, causes the electrons to converge upon the specimen held a few centimeters below it. The condenser, like the condenser lens of a light microscope, can be used to control the angular aperture of the illumination at the specimen.

After passing through the specimen, the electrons enter the objective lens (*c*). This lens deflects the electrons leaving the specimen in such a way as to focus them into a magnified intermediate image of the specimen. This image is formed directly above the projection lens (*d*). The objective, like the condenser, is an armored coil, but the pole pieces are, of course, different in design to meet the requirements of this element. The design of the object lens is very important, and the success or failure of an electron microscope depends to a large extent upon the skill and accuracy with which it is designed and constructed.

The final image is formed from the por-

Figure 3. Air lock and object chamber

tion of the intermediate image which passes through the projection lens (d) and is reimaged in the plane of the observing screen or photographic plate at (e). The magnification of the intermediate image is about 100 diameters, and the magnification by the projection lens can be varied between 20 and 300 diameters; therefore the total magnification can be controlled over the range between 2,000 and 30,000 diameters. The maximum electronic magnification of the microscope is two or three times less than the greatest useful magnification corresponding to the resolving power of the instrument, the full useful magnification, for reasons that are discussed below, being obtained by additional photographic enlargement. When visual observation of the specimen is required, the final image is allowed to fall on a fluorescent screen. This screen can be raised out of the way to permit the image to impinge upon a photographic plate for a permanent record, or for more detailed examination.

Since electrons will not travel freely through air, the entire electron optical path of the microscope must be under vacuum, that is, at a pressure of about 10^{-5} millimeters Hg. All permanent joints are brazed or soldered so that they are vacuum-tight without the aid of sealing compounds. The demountable joints, such as those between the electron lenses and the microscope chambers, are sealed with Neoprene, and are arranged in such a way that the alignment is maintained by metal-to-metal contacts rather than by the metal-to-plastic contacts. At certain points in the microscope, parts must be movable with respect to one another in order to permit alignment. Such parts are jointed by flexible metal bellows so the adjustments may be made while the microscope is under operating conditions. No greased joints are used in the microscope.

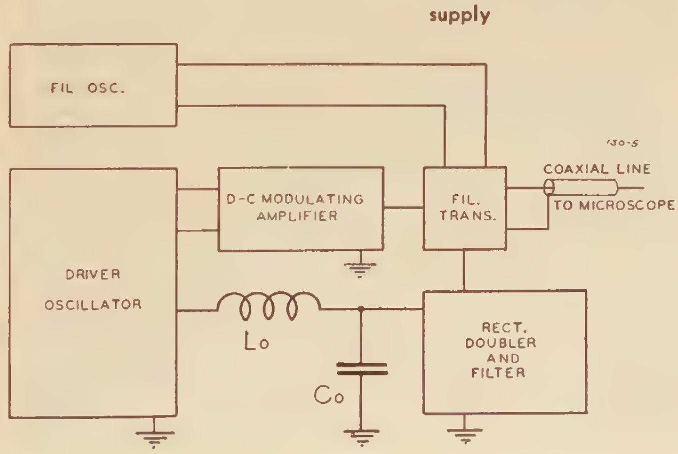
If it were necessary to repump the entire microscope every time a specimen or photographic plate is changed, it would greatly curtail the speed of operation of the instrument. Consequently air locks are provided which permit making these changes without breaking the main vacuum. The air lock for the object chamber (e) is shown in figure 3. A handle at the rear of the chamber raises the object from its position over the objective, moves it into the air lock, and closes the latter off from the main chamber of the microscope. A second handle admits air to the lock and opens it so that the object may be removed. When the object is replaced, the second handle closes the air lock, connects it with an auxiliary pump for a preliminary exhaust, and then seals it off. With the first handle, the specimen is moved back into the microscope to its original position.

The photographic chamber, which is shown in figure 4, is arranged with a similar air lock. The photographic plate used with the microscope is about ten by two inches in size. The long plate permits making a number of exposures on the same plate. An adjustable mask governs the width of the pictures.

The microscope pumping system con-

Figure 4. Photographic chamber

Figure 5. Block diagram of high-voltage supply



sists of a three-stage oil diffusion pump (l), in figure 2, which is connected to the main chamber of the instrument through the manifold (m). This pump is backed up by a mechanical fore pump. A second auxiliary mechanical pump is used to exhaust the two air lock chambers.

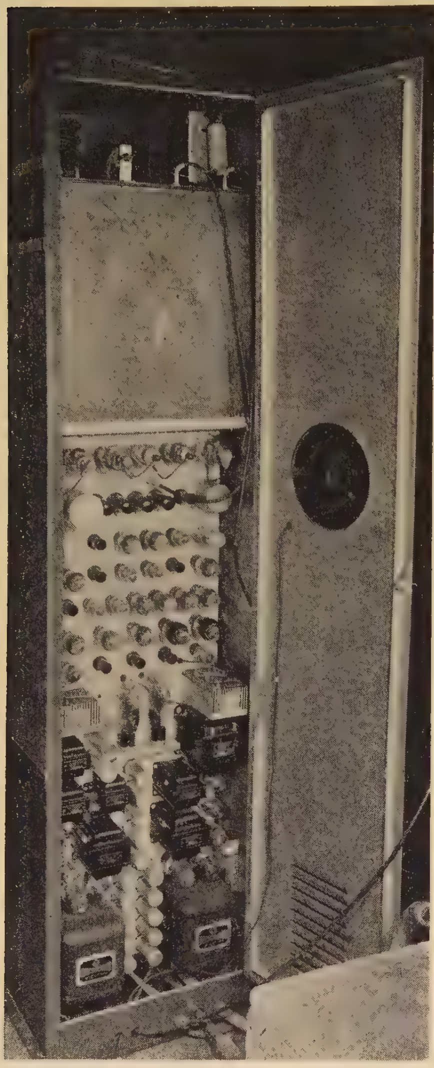


Figure 6. Rear of microscope showing power supply and regulator units

It can be shown that the focal length of a magnetic electron lens depends upon the current through the lens coil and the velocity of the electrons themselves. This means that the high-voltage supply and the lens current sources must be very free from fluctuations. In order to obtain a resolving power of 10^{-7} centimeters it is found that the following stabilities are required:

Over-all microscope voltage	0.015	per cent
Objective current	0.0075	per cent
Projection lens current	0.068	per cent
Condenser lens current	0.1	per cent

The problem of obtaining 60 kv with the required degree of constancy in the small space available is both difficult and interesting. The high-voltage supply, which was designed by A. W. Vance, employs radio-frequency power rather than the conventional 60-cycle power to actuate the step-up transformer unit.[8] This results in a number of advantages. A low-loss resonant coil can be used which occupies only a small volume and requires only a small exciting power. Much smaller condensers can be used for a given allowable amount of ripple. A regulator operating on the low-voltage side of a rectifier is limited in its speed of regulation by the frequency of the power supplied. At radio frequency, this limitation becomes unimportant. Finally, stray fields, which are difficult to shield at 60 cycles, are easily shielded when radio frequency is used. It is, therefore, possible to mount the power supply close to the microscope as an integral part of the unit.

A block diagram of the high-voltage unit is given in figure 5. The basic circuit consists essentially of a high-Q resonant net which presents series resonance to the driving oscillator, and is parallel resonant to the high-voltage output rectifiers. The resonant circuit consists of coil L_0 and the effective lumped capacity C_0, which is made up of the rectifier capacitance and stray capacities. To obtain a given output voltage, the exciting power required from the oscillator, since the load is very small, depends upon the Q of the circuit and the resonant impedance of the high-voltage coil. Great care must be used in the design of the coil and in the selection of operating frequency in order to obtain a high Q and maximum impedance. The actual frequency selected is 32 kilocycles, and the Q of the resonant circuit is about 200. The exciting power required to produce the desired power is about 150 watts, and the maximum load in the neighborhood of 30 watts.

Since the Q of the resonant circuit is high, the driving frequency from the oscillator must be exactly correct if large inefficiencies are to be avoided. In order to maintain the correct driving frequency, the frequency oscillator is controlled by the resonant circuit itself. The output voltage of the power supply is governed by the amplitude of the current from the oscillator. This, in turn, is varied by the screen-grid voltage applied to the oscillator output tubes. By controlling the screen voltage, not only can the output voltage be set at any desired value, but also the constancy of the voltage can be governed.

The rectifier across the resonant circuit is arranged to give voltage doubling. The type of doubler used permits grounding one side of the high-voltage coil, thus permitting the use of a simple resonant circuit rather than a tuned transformer.

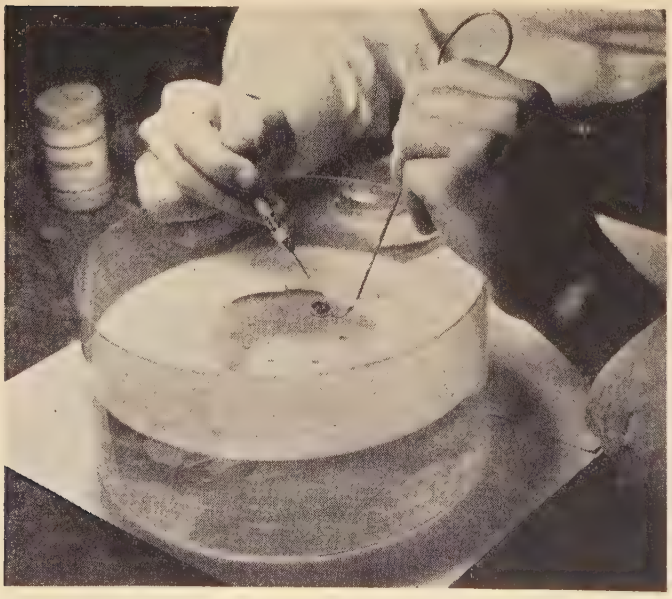


Figure 7. Preparation of supporting films for specimens

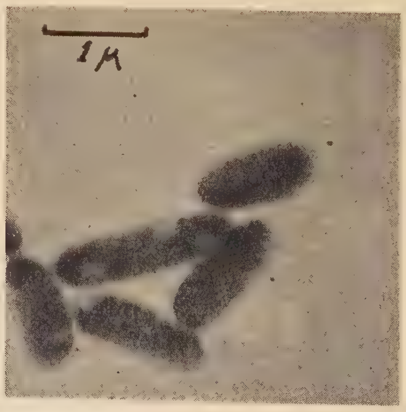


Figure 8. Micrograph of pseudomonas aeruginosa bacteria. Magnification 14,000 diameters

Figure 9. Micrograph of slightly polymerized vinyl chloride. Magnification 77,000 diameters

Figure 10 (right). Micrograph of polymerized vinyl chloride. Magnification 100,000 diameters

The high-frequency ripple is eliminated from the high-voltage output by means of a tuned filter. Low-frequency disturbances are removed by comparing a fraction of the output voltage obtained from a special divider with a standard voltage,[4] and controlling the oscillator screens by means of a d-c amplifier. Such a feedback regulator, when certain necessary precautions are effected, is capable of extreme constancy. The measured voltage fluctuation over a period of 30 minutes is less than 0.002 per cent in the actual microscope power supply.

The current supplies for the three lens coils are controlled by very sensitive regulators. These regulators make use of well-known principles, and will not be discussed here.[4] By careful design and the use of a number of special refinements, these current sources have a constancy of better than 0.002 per cent for the objective lens, 0.004 per cent for the projection lens, and 0.02 per cent for the condenser lens.

The complete power supply is assembled in a cabinet which forms the back part of the microscope unit. The lens current sources and the oscillators are located at (*e*) in figure 2. The high-voltage coil, rectifiers, and filters are immersed in the oil tank (*f*). Short, corona-proof leads carry the high voltage to the gun of the microscope. All power supplies are completely interlocked to insure absolute safety, and protective relays are arranged to open the high-voltage circuit in event that vacuum conditions within the microscope are not right. Figure 6 is a photograph of the rear of the instrument with the door to the power-supply section open so that the general arrangement of the equipment can be seen.

The operation of the instrument is simple in the extreme. The operator seated in the observers' position can reach the electrical controls and thus adjust overall voltage, magnification, or focus, while watching the image. In addition, the specimen can be moved in two directions in a horizontal plane, so that any portion of the object may be brought into the field of the microscope. Six ports are provided for viewing the final image, and, in order to permit initial orientation of the specimen, three small windows allow direct observation of the intermediate image.

To record the image photographically, it is only necessary to move the plate into position under the fluorescent screen, and then to raise the screen so that the electron image falls on the plate. The fluorescent screen is designed to serve as the shutter for timing the exposure. It is expedient when making electron micrographs to use as low an electronic magnification as possible, and to obtain the

Figure 11. Micrograph of commercial chemical. Magnification 150,000 diameters

Displacement and Diffusion in Fluid-Flow Arc Extinction

JOSEPH SLEPIAN
FELLOW AIEE

Synopsis: The displacement and diffusion theories of arc extinction in flowing fluids are defined and contrasted. The question as to the possibility according to hydrodynamical principles of the formation of the wedge required by the displacement theory is considered and decided in the negative. Photographic evidence is also found to contradict the displacement theory. How turbulence will multiply diffusive effects is considered, and an estimate of 100fold multiplication is given for conditions existing in gas blast breakers. This enhancement of diffusion by turbulence is found to make the diffusion theory adequate for accounting for the circuit interrupting capacities of arcs in gas blast circuit breakers.

I. Introduction

THE important large effect which motion of the circumambient fluid has upon the circuit interrupting ability of an a-c arc has long been known, but there are still widely diverging theories as to how this effect comes about. Slepian,[1] in discussing the influence of gas motion in self-generating gas blast devices such as oil circuit breakers and expulsion fuses stressed the effect of turbulence in causing a more rapid mixing of hot and cold gas volumes, thus speeding the spread of heat, and a more rapid mixing of highly ionized with unionized gas volumes, thus speeding the dilution of the ions into larger volumes. The theory here, then seems to have been that the function of the gas motion is to intensify or enhance diffusive effects, and more particularly, thermal conduction and ion diffusion. This type of theory which makes the powerful arc extinguishing effect of the fluid flow depend entirely upon its creating conditions where diffusive effects are greatly enhanced shall be called in this paper the "diffusion theory".

A radically different theory of the extinguishing effect of the fluid flow was advocated by Prince,[2,3] which shall be called in this paper the "displacement theory". This theory states that at current zero (or perhaps at a moment very near to current zero), the physical continuity of the arc is broken at some obvious geometrical point, by the interposition of a small quantity of *cool, un-ionized,* and *dielectrically completely sound* fluid. From this moment on, the dielectric strength of the arc space is completely given by the dielectric strength of this interposed fluid. The relative velocity of the two ends of this interposed fluid is believed to be one or sometimes two times the mean velocity of the fluid in that neighborhood. Thus the thickness of the interposed fluid grows rapidly, being given by the product, vt, of the fluid velocity and the time. The rate of growth of the total dielectric strength of this interposed fluid in volts per second, will be given by Xv, where X is the intrinsic dielectric strength of the interposed fluid in volts per centimeter, and v is the fluid velocity in centimeters per second. Arc extinction thus is said to depend on whether or not this rate of recovery of dielectric strength of the interposed fluid exceeds the so-called "recovery rate" of the circuit. That is the arc will be extinguished if

$$Xv > \frac{dV}{dt}$$

where $\frac{dV}{dt}$ is the circuit "recovery rate" in volts per second.

Apart from whether the "displacement theory" is correct or not, it has the incontestable advantage that it leads directly to an attractively simple equation, so that the designer or user of a circuit breaker who accepts this theory may have the comforting assurance that the breaker performance has been "calculated". Hap-

Paper 40-115, recommended by the AIEE committee on protective devices and presented at the AIEE Pacific Coast convention, Los Angeles, Calif., August 27-31, 1940. Manuscript submitted March 27, 1940; made available for preprinting July 9, 1940.

JOSEPH SLEPIAN is associate director of research, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

1. For all numbered references, see list at end of paper.

---

full useful magnification by photographic enlargement of the plates. In general, a photographic enlargement of six to ten times can be made without bringing out the grain of the emulsion. Therefore, if the total useful magnification required is 100,000 diameters, the electronic magnification will be 10,000 to 16,000. The advantages of this procedure are that it decreases the exposure time, reduces the bombardment to which the object must be submitted, and increases the useful field of view of the microscope.

The specimens themselves are mounted somewhat differently from those used with a light microscope. Glass slides would be completely opaque to electrons; therefore the objects to be examined are mounted on extremely thin cellulose films, supported by a fine wire mesh. The method of preparing one of these supporting films, which are only about 0.000001-centimeter thick, is illustrated in figure 7. The material or particles to be studied are usually suspended in water or some other suitable liquid, and a drop of the suspension is placed on the film. After the liquid has evaporated, the specimen is ready for use.

The utility of this instrument is almost unlimited, and it finds applications in many fields of scientific and industrial research. Two fields, chosen at random, serve to illustrate its value. In bacteriology and biology it opens up new and entirely unexplored realms, for with this microscope microorganisms such as viruses, which cannot even be seen with an optical instrument, can be studied in detail. Figure 8 is a typical micrograph of pseudomonas aeruginosa bacteria. Much of the structure seen in this photograph is well below the resolving power of an ordinary microscope. In physical chemistry it can be used to study colloids, point reactions, the structure of thin films, and even large organic molecules. To illustrate this application, micrographs of slightly polymerized and polymerized vinyl chloride films are shown in figures 9 and 10. The final photograph illustrates a commercial chemical product. Structure of less than 50 angstrom units can be resolved in this micrograph.

References

1. A New Electron Microscope, L. Marton. *Phys. Rev.*, volume 58, number 1 (July 1, 1940), pages 57–60.

2. Electrons Extend the Range, V. K. Zworykin. Electrical Engineering, volume 59, November 1940, pages 441–3.

3. Recent Developments in the Electron Microscope, J. Hillier and A. W. Vance. *Proc. I.R.E.*, 1941.

4. Stable Power Supplies for Electron Microscopes, A. W. Vance. *RCA Review* (January 1941) volume 5, pages 293-300.

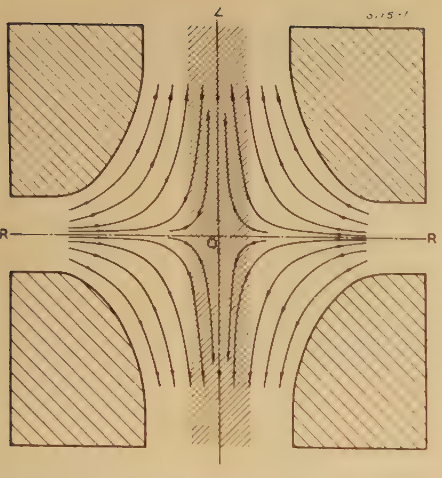


Figure 1. Ideal flow in a double nozzle

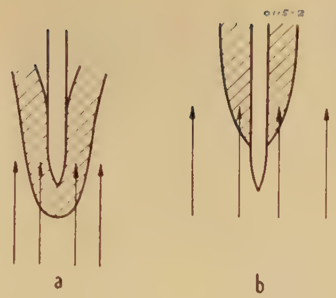


Figure 2 (left). Wedge formation at sharp splitter in ideal fluid

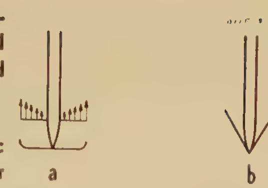


Figure 3. Bending of an arc around a gas-forming splitter

pily, however, designers of breakers "calculated" in this way have not dispensed with thoroughgoing high power laboratory tests, so that the performance of such breakers rests on a more solid foundation than the "calculation".

European investigators have advocated both the diffusion and displacement theories. O. Mayr[4] quite definitely makes diffusive effects the dominating factor in determining arc extinction, but Kesselring and Koppelmann[5] principally because they are not able to calculate a sufficiently large interrupting effect on the basis of diffusion, espouse the displacement theory. However, in their calculations which at best can only be regarded as giving orders of magnitude, because of the uncertainty of our present knowledge of the fundamental processes going on in the rapidly changing arc, Kesselring and Koppelmann underestimate completely the great enhancement of diffusive effects arising from even only a moderate degree of turbulence.

Holm, Kirschstein, and Koppelmann[6] speak of the effect of gas motion and its turbulence in increasing the thermal losses from the arc during the current conduction period, but do not take into account the effect of turbulence in increasing ion loss by enhanced diffusion. Also, surprisingly, although they seem to recognize the importance of turbulence during the conduction period, in the "currentless pause" (stromlose pause) near current zero they use for the thermal conductivity and ion diffusion coefficient numbers appropriate to a gas at rest, and overlook the great increase in these quantities arising from the gas motion. Thus they greatly underestimate the voltage interrupting capacity of an arc of small section at current zero.

These last authors also speak of the possibility of a cutting of the physical continuity of the arc, but state at once that such cutting cannot happen, *loc. cit.*, page 84, but that rather a configuration favorable for rapid diffusion occurs where one might naively suggest a cutting. With this exception, none of the references just mentioned question whether accepted hydrodynamical principles will permit the formation of a growing wedge of sound fluid interrupting the continuity of the arc.

II. Impossibility of Wedge Formation in Interior of Ideal Fluid—Diffusion Absent

To see clearly why hydrodynamical principles forbid the formation of an interrupting wedge, consider the flow of an ideal fluid pictured in figure 1. This portrays a flow corresponding to the double nozzle discussed by Kesselring and Koppelmann. We choose an ideal fluid, that is, one with zero viscosity, because we wish to exclude diffusion effects, and viscosity is a consequence of diffusion, namely the lateral diffusion of molecules from faster moving regions into slower moving regions, and vice versa. For simplicity in calculations let us assume the fluid incompressible. A little thought soon convinces one that compressibility does not alter the conclusions reached.

In figure 1 we have fluid flowing inward radially through a circumferential opening, and axially out along the Z axes through a double nozzle. At the time $t=0$, we fix our attention upon the column of fluid shown shaded, which might be the arc configuration near current zero. However, to keep the flow considered simple, let us assume that the shaded column of fluid has the same density as the rest of the fluid, and not a much lower density as in the high temperature arc. We may perhaps regard the shaded column of fluid marked with a non-diffusing ink giving a negligible density change in the fluid.

One might imagine from inspection of the figure, that as the flow proceeds, the shaded column would be broken or cut in two, and that presently the two newly formed ends would be receding from each other with twice the axial fluid velocity through the nozzles. However, a little calculation shows that this is not at all the case. In the neighborhood, O, of the geometrical center of the figure, the axial velocity is given by

$$v_z = Az \tag{1}$$

where z is the distance along the axis from O, and A is a constant, and the radial velocity, is given by

$$v_r = \frac{dr}{dt} = -\frac{1}{2}Ar \tag{2}$$

where r is the distance from the central axis. These equations will hold approximately out to distances approaching the nozzle dimensions.

The bounding cylindrical surface of the shaded region will be described by the equation,

$$r = r_0 \tag{3}$$

at $t=0$.

The subsequent motion of this bounding surface will be obtained by integrating equation 2. We obtain at once,

$$r = r_0 e^{-{}^1/_2 At} \tag{4}$$

The cylindrical surface remains cylindrical, but its radius approaches zero at a constantly diminishing rate. There is no formation of a surface with two nappes; no interrupting wedge appears. The length of this cylindrical column of constantly diminishing radius will be comparable with the nozzle dimensions.

To get some quantitative ideas of the rate of thinning of the cylindrical column, let the axial velocity of the fluid be $3 \cdot 10^4$ centimeters per second at 1 centimeter from O then $A = 3 \cdot 10^4$. Then equation 4 becomes

$$r = r_0 e^{-\frac{t}{66.7 \times 10^{-6}}} = r_0 2^{-\frac{t}{45.2 \times 10^{-6}}} \tag{5}$$

We see that the column has its radius halved each 45.2 microseconds, but the radius never becomes actually zero.

If we assume no diffusion takes place, the density of the ink marking the thinning column remains unchanged. Applying the ideas developed here to the arc, we see that pure streaming, without diffusive effects, will thin the arc, but will not change its temperature or ion density, and therefore will not change its dielectric strength per unit length.

III. Enhanced Diffusion Responsible for Interrupting Effectiveness of Axial Flow

The preceding section has made clear that without diffusion (of which thermal conductivity and viscosity are consequences), axial streaming of the fluid as in a double nozzle can have no interrupting effect upon the alternating current arc near current zero. All it can do is to cause the radius of the arc stream to shrink asymptotically to zero, with no change in ion density or temperature of the arc space.

However, it is evident that this effect of the motion of the fluid in reducing the arc diameter can play an important part in increasing greatly the interrupting effect of such diffusive forces as are intrinsically present. The time constant for diffusion from a cylindrical region, that is, for example the time for the ion density to be reduced to one-half, or the time for the temperature to fall to one-half, varies as the square of cylinder diameter. Thus, in the numerical example given in the preceding section, the rate of ion loss, and the rate of cooling will multiply by 4 every 45.2 microseconds, during the interrupting period, due to the reducing arc diameter.

However, this is far from the whole story. As Kesselring and Koppelmann[5] have shown, taking the small arc diameters such as are actually observed at current zero in the double nozzle flow, ordinary diffusion and thermal conduction are still not great enough to account for the observed interrupting effect. The high interrupting capacity comes because there is inevitably a high degree of turbulence in the axial flow through the arc.

In the example discussed in the preceding section and pictured in figure 1, the velocity in the incompressible ideal fluid varies in space according to equations 1 and 2. By Bernouilli's principle, the pressure in the fluid will vary in space according to the equation

$$p_0 = p + \frac{1}{2}\rho(v_z^2 + v_r^2) \tag{6}$$

where p_0 is the pressure at 0, the point of zero velocity. At each point, the velocity is determined by the fall in pressure to that point, but it should be observed that for a given pressure distribution, the velocity will vary inversely with the square root of the density of the fluid.

But now suppose that the shaded cylinder of figure 1, instead of having the same density as the rest of the fluid, has a density, like that of an arc, only $^1/_{20}$ or less, of the density of the surrounding fluid. The pressure distribution must remain continuous. Hence at any particular distance from O, the velocity in the arc would need to be $\sqrt{20}$ or more times the velocity of the adjacent cool and more dense fluid. There would have to be then a sharp discontinuity in fluid velocity, and enormous shearing stresses at the arc boundary due to viscosity. What happens under such conditions is that the smooth streamline flow portrayed in figure 1, is replaced by an intensely turbulent flow through the arc, the kinetic energy of the turbulence adding itself to the kinetic energy of the average motion to give a total velocity head compatible with Bernouilli's equation 6.

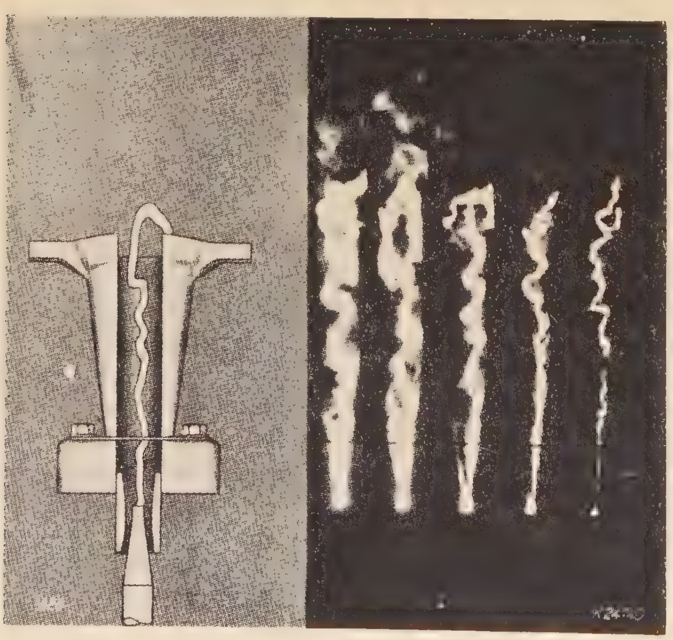
As we shall see in section VI, this high degree of turbulence functions to further greatly increase the rate of cooling and deionization of the arc stream at current zero, and probably fully accounts for large interrupting capacity of the axial flow.

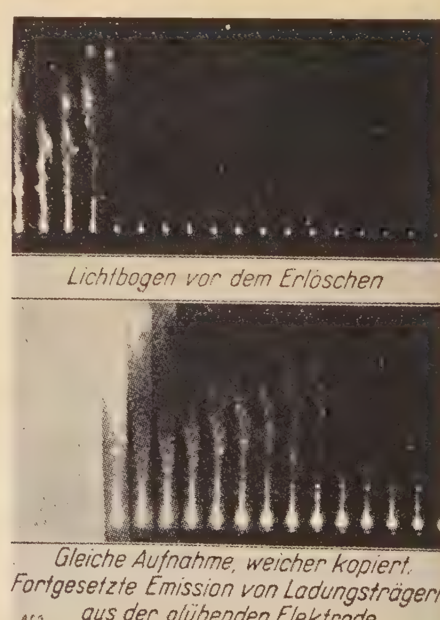
IV. The Cross Blast—Wedge Formation at a Splitter

Compressed air circuit breakers have been recently introduced[7] in which the arc is blown transversely against several splitters made of gas forming material. Let us examine what may happen to an arc column at such a sharp splitter.

Under the influence of the fluid motion, the arc is lapped round the sharp splitter in a thin column as current zero is approached as in figure 2*a*. What does the further motion of the fluid do to this column? Photographic records show that the thickness of this column is too great for simple diffusion or thermal conductivity to account for the high interrupting capacity actually found. Does the moving fluid cause the column to be cut, and introduce between the cut ends a longer and longer path through good dielectric? Or does the fluid motion so enhance diffusive effects that even the relatively thick long column cools and deionizes quickly enough to have a high interrupting capacity?

If the fluid is ideal, with zero viscosity (and therefore also with zero thermal conductivity and zero ion diffusion), the answer is certainly that the arc column is cut as in figure 2*b*, with the recovered dielectric strength equal to that of the path through the introduced fluid between the cut ends of the arc column. The displacement theory then will apply. But





Figures 4 (left) and 5 (right). High-speed motion pictures by Biermanns

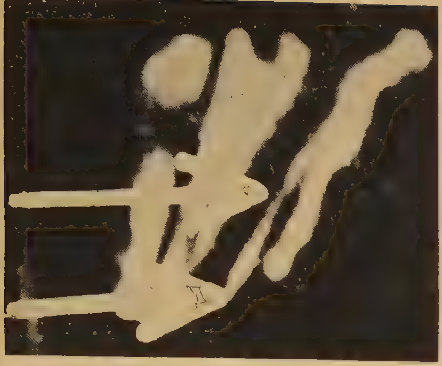


Figure 6. Arc against splitter, by Prince

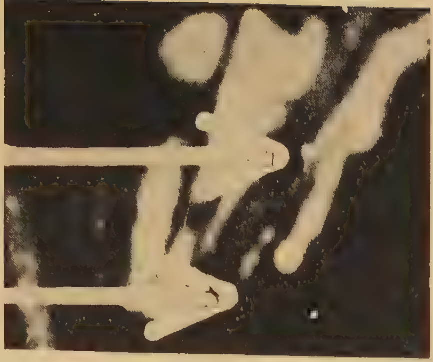


Figure 7. Arc against splitter, $16^2/_3$ microseconds after figure 6

Figure 8. Arc against splitter, $16^2/_3$ microseconds after figure 7

the fluid will need to flow with its full velocity parallel to and right up to the splitter wall.

However, actual fluids cannot flow in this manner. Even with very small viscosity, the fluid velocity next to the splitter wall must be zero. Otherwise infinite shearing stresses would be exerted on the fluid and wall. A layer is formed next to the splitter wall, in which the fluid velocity varies from zero at the wall, to the full streaming velocity away from the wall. In this boundary layer, the shearing stresses arising from viscosity are large compared with the inertial forces.

With homogeneous fluid, the boundary layer starts with zero thickness at the splitter edge, and grows in thickness upstream from the edge. In this first part of the boundary layer, the flow is laminar, but at some point far enough upstream the flow in the boundary layer becomes turbulent, and the boundary layer thickness then increases more rapidly.

For air, at high velocity, and with a well designed splitter, such as an air-foil, the boundary layer a few centimeters upstream is only a few thousandths or a hundredth of a centimeter thick. We might imagine then that figure 2 could be corrected by drawing such a thin boundary layer joining the two receding ends of the cut column. Since so thin a boundary layer would cool and deionize exceedingly rapidly, this correction would not seriously change the conclusions of the displacement theory.

However, in the actual circuit breaker, we do not have a homogeneous fluid flowing past the splitter, but the density of the arc column is only one-twentieth that of the flowing air. We may expect then that the boundary layer will start in a turbulent state from the very beginning at the splitter edge. Still further complicating the situation is that under the heat of the arc, the splitter material gives off gas at a high rate, this gas evolution continuing right through current zero. This gas projected out from the wall will certainly widen the boundary layer enormously, and make it wide even at the beginning of the splitter. But with a wide boundary layer, the displacement theory fails completely since a wedge of fresh fluid interrupting the arc growing with the full streaming velocity of the fluid cannot form. The arrows in figure 3*a* are intended to show by their length the mean velocity distribution in the boundary layer. We fix our attention on the horizontal line just touching the splitter edge, and which we suppose moves with the fluid. This line may represent a bounding surface of an arc column near current zero. A finite time later the line will look as in figure 3*b*. Because of the zero velocity at the splitter surface, the line is bent, but not cut.

V. Photographic Evidence Concerning Displacement Versus Enhanced Diffusion

High-speed motion pictures taken of arcs being extinguished in axial and cross blasts offer valuable evidence for determining whether the displacement or enhanced diffusion theory is correct. J. Biermanns[8] shows pictures taken at 5,000 per second of an arc blown through a single nozzle. Figures 4 and 5 are examples taken from Biermanns' paper. Extinction seems to have taken place after the fourth picture in figure 5. If the displacement theory were correct we would expect to see in the fifth picture a completely dark break in the continuity of the luminous arc, and this break should be at most $200 \cdot 10^{-6}$ second, the time interval between pictures, multiplied by the probable velocity, about $3 \cdot 10^6$ cm, or about 6 cm. Actually, in the fifth picture of the lower half of figure 6, there is a length of about this magnitude which is darker than the rest, but it is not completely dark, and also there are in it several splotches which are more intensely luminous. If this darker length does represent the growing wedge introduced into the arc according to the displacement theory, we must conclude that this wedge far from being fresh dielectrically sound fluid, is considerably contaminated by inmixing of ionized and radiating gas from the arc itself. This contamination, which is evidence of considerable turbulence, should be extremely great when the wedge is short, thus making it impossible to speak at all of a short wedge of nearly fresh dielectrically sound fluid. It is only after the "wedge" is of considerable length that it can have decontaminated itself so that it can be regarded as being of dielectrically sound material. This decontamination, however, according to section II can proceed only from diffusion, so that we are driven inevitably to the diffusion theory according to which a considerable length of the arc column finds itself in a condition so favorable for rapid diffusion that it recovers dielectric strength sufficiently rapidly to effect circuit interruption.

Comparison of the upper part of figure 5 with the lower which was obtained from a photographic print with much less contrast, also gives evidence of diffusion much intensified by turbulence. The sharply defined intensely luminous arc column in upper figure 5 is revealed in lower figure 5 as surrounded by less luminous gas which must have diffused rapidly out of the arc column.

Prince[7] has shown some extraordinary pictures taken at 60,000 per second of a circuit interruption by an arc in a cross air blast against fiber splitters. Three of these successive pictures, which are believed by the present author to include the moment of circuit interruption are reproduced here as figures 6, 7, and 8. In figure 6, the arrows introduced by this author point out the two-inch length of arc which he believes to have been responsible for the circuit interruption. This length of arc lies squeezed up against the splitter surface. At the splitter surface itself, the mean velocity of the gas

in the arc parallel to the surface must be zero. At the other boundary of the arc, the non-luminous air is moving with very high, probably acoustic velocity. The velocity gradient is then very large in this arc. Also, there is a very sharp change in gas density at the boundary of the arc. Lastly, gas from the decomposing splitter is being projected perpendicularly into the arc column. All these factors must create an intense turbulence, which must so enhance diffusion that these two inches of arc are cooled and deionized extraordinarily rapidly.

In any case, figure 7 shows that after only $16^2/_3$ microseconds the two inches have lost most of their luminosity, and in figure 8, after another $16^2/_3$ microseconds the luminosity has almost completely disappeared. If we assume acoustic velocity of $3 \cdot 10^4$ cm per second, the fluid displacement in $16^2/_3$ microseconds would be only $^1/_2$ cm. This is very small compared to the two-inch length of arc column which seems to be the first less luminous break to make its appearance in the succession of pictures. Thus these high speed pictures of Prince support strongly the enhanced diffusion theory as against the displacement theory.

VI. Turbulence and Enhanced Diffusion

Appreciation of the fact that fluid motion enhances diffusion is as widespread as the custom of accelerating the sweetening of coffee by stirring with a spoon. Recent developments in the theory of turbulence, however, now make it possible to give a rough numerical measure to this degree of enhancement.

When a sufficiently small dimensioned measuring instrument is used, the velocity at a given point in a steadily streaming fluid is found to be not constant, but to have very rapid variations in magnitude of an apparently random character. Thus figure 9 shows the velocity reading obtained by Dryden[9] in a wind tunnel with a hot wire anemometer made of Wollaston wire, 0.008 mm (0.0003 in.) in diameter. This rapidly varying deviation, u, from the mean velocity U is called the turbulent velocity, and its root mean square with respect to time, $\sqrt{\overline{u^2}}$, is called the intensity of the turbulence. The ratio of the turbulence intensity to the mean velocity in figure 9, according to Dryden is as much as nearly 0.01, even in a wind tunnel where every effort is made to eliminate turbulence as far as possible. In the cases discussed in the previous section the ratio of the turbulence intensity to the mean velocity

Figure 9. Turbulence in a wind tunnel, by Dryden

Turbulence of wind tunnel, $\sqrt{\overline{u^2}}/U = 0.0085$. Time = 0.4 second approximately. Relative amplification = 64

must be very much greater. One, or an even greater number, would seem to be a not unreasonable figure for this ratio. We may then certainly take 10,000 cm per second as a conservative estimate of the intensity of turbulence in the arc columns placed in rapidly streaming fluids in the examples discussed in the previous sections.

The turbulence may perhaps be pictured as a large number of small eddies or vortices superimposed on the average smooth motion of the fluid. These eddies are of constantly changing size, and velocities, but in a steady state of flow show a statistical constancy. To reveal the turbulent motion, the velocity measuring instrument must have dimensions small compared to the geometrical dimensions of the individual eddies.

This picture suggests how turbulence may bring about diffusion. A very small portion of the fluid upon which we fix our attention, takes part in the motion of an eddy. A moment later, however, it is part of another eddy, having a different center. It can thus wander from eddy to eddy, off the average flow lines of the fluid. But such motion we call diffusion.

A great similarity will be noted between this picture, and the picture of diffusion in a stationary gas offered by the kinetic theory of gases. According to this kinetic theory, even for a gas at rest, the individual molecules have velocities which are random in direction and magnitude. The mean random speed, c, of the molecules is of the order of acoustic velocity of the gas, or for normal air $3 \cdot 10^4$ cm per second.

The motion of a molecule moving in any particular direction will be arrested and changed into other random directions by collisions with other molecules. Thus the individual molecule will wander about in space in a random manner. This random wandering is molecular diffusion.

The speed with which a particular molecule wanders away from any particular fixed point in space will depend on the average absolute speed of the molecule, c, but it will also depend on the average distance the molecule goes before making a collision which changes the direction of its motion, that is the mean free path λ. The diffusion coefficient for the molecule, according to elementary kinetic theory is given by

$$D_m = \frac{1}{3} c\lambda \tag{7}$$

In looking for an analogous expression to estimate the diffusion coefficient arising from turbulence, we already have a factor which would seem to correspond to the molecular speed, c, namely the turbulence intensity $\sqrt{\overline{u^2}}$. What will correspond to the mean free path λ? Most plausibly, the average eddy size!

G. I. Taylor[10] has recently shown how from measurements of the turbulent velocity, u, a length may be determined of just this character. Taylor considered the correlation coefficient between the turbulent velocities, u_1 and u_2 at two nearby points in the moving fluid. The correlation coefficient is defined as

$$R = \frac{\overline{u_1 u_2}}{\sqrt{\overline{u_1^2}}\sqrt{\overline{u_2^2}}} \tag{8}$$

The dashes above the functions of time in equation 8 signify that the average with respect to time of the functions must be taken.

It may be shown mathematically that if two functions u_1, u_2, have a correlation coefficient R equal to unity, then the two functions must be completely identical in form, that is $u_1 = ku_2$, where k is a constant. On the other hand, if the two functions are completely unrelated, then u_1 is as likely at any moment to differ in algebraic sign from u_1 as to agree with it, and $\overline{u_1u_2}$ and therefore R will be zero.

If the two points, 1, 2, being considered stayed always on the same eddy, then $u_1 = ku_2$, and $R = 1$. On the other hand if the points 1, 2, are always on different eddies, then u_1 and u_2 are completely unrelated, and the correlation will be zero, $R = 0$. The actual correlation R for two points, which will generally have a value between 1 and 0, may be regarded as measuring the fraction of the time the two points are on the same eddy.

The correlation coefficient may be directly measured by the use of appropriate electrical circuits used in conjunction with very fine hot wire anemometers. Figure 10 shows the correlation coefficient obtained by Dryden[9] as a function of distance of the second point from the first in turbulence produced in a wind tunnel by screens of different mesh sizes. As might be expected when the two points are very close together, the correlation

coefficient is unity, and when they are far apart it is zero. The distance in which the correlation coefficient drops to zero gives a measure of the average eddy size.

Taylor[10] defined a turbulence scale factor

$$L = \int_0^\infty R\,ds \tag{9}$$

where s is the separation of the two points. L may be regarded as the average eddy size, and should be the analogy of the mean free path λ, in the kinetic theory of molecular diffusion. From figure 10, we see that in the turbulence measured by Dryden, the scale factor is of the same order of magnitude as the mesh sizes of the screens producing the turbulences.

Leaning on the analogy with the kinetic theory of molecular diffusion in gases at rest, and referring to equation 7, we arrive at the strong expectation that the effective diffusion coefficient, D_t, due to the turbulence should be given by

$$D_t = B\sqrt{\overline{u^2}}\,L \tag{10}$$

where B is a constant not very small compared to unity. The ratio of D_t to D_m may then be expected to be of the order of $\sqrt{\overline{u^2}}L/c\,\lambda$. We have just seen that c is of the order of acoustic velocity, and that in practical gas blast circuit breakers $\sqrt{\overline{u^2}}$ is also of the order of 10^4 cm/second λ, under normal gas conditions is of the order of 10^{-5} cm. What magnitude shall be taken for L?

Referring again to figure 10, which shows that the turbulence scale factor has about the same magnitude as the scale of the physical structure responsible for the turbulence we are led to expect that in the gas blast circuit breaker, L, will be about the same as the dimension of the arc section. Near current zero, in the axial flow breaker, this is about 10^{-1} cm, and for the cross blast breaker, with gas forming splitters, it is considerably larger. We find, then, with respect to order of magnitude,

$$D_t/D_m = B\sqrt{\overline{u^2}}L/{}^1/_3 c\lambda$$
$$= 10^4 \cdot 10^{-1}/10^4 \cdot 10^{-5} = 10^4 \tag{11}$$

Thus we see that under the conditions occurring in gas blast breakers the intense turbulence brings about an enormous multiplication of the effective diffusion coefficient. Even allowing for all the looseness in dealing only with orders of magnitude, we see that a 100fold enhancement of diffusion effects is not an unreasonable expectation.

This means that all the factors contributing to arc extinction, such as ion diffusion and cooling by thermal conduction are also multiplied 100fold. The difficulty then which Kesselring and Koppelmann[4] experience in adequately accounting for the interrupting capacity on the basis of diffusive effects alone, disappears.

VII. Summary

1. The displacement and diffusion theories of a-c arc extinction in rapidly flowing fluids are contrasted.

2. The formation, in the interior of a streaming perfect fluid, of the wedge required by the displacement theory is shown to be impossible according to accepted hydrodynamical theory.

3. The formation, at the edge of a gas forming splitter in a cross blast, of the wedge required by the displacement theory is shown to be impossible according to accepted hydrodynamical theory.

4. High speed motion pictures of arcs extinguished in gas blasts are shown to contradict the displacement theory and support the diffusion theory.

5. Rough calculations are given which show that the turbulence which may be expected to exist in the extinguishing arc in gas blast breaker, may multiply diffusive effects by 100 or more.

6. This multiplication of diffusive effects is stated to be sufficient to make the diffusion theory adequate for accounting for the high interrupting capacity of gas blast circuit breakers.

References

1. J. Slepian, AIEE Transactions, volume 49, 1930, pages 421–30; *Journal* of the Franklin Institute, volume 214, 1932, pages 413–42.

2. D. C. Prince and W. F. Skeats, AIEE Transactions, volume 50, 1931, pages 506–12.

3. D. C. Prince, AIEE Transactions, volume 51, 1932, pages 166–70.

4. O. Mayr, *E.T.Z.*, volume 53, 1932, pages 75–81; *Bull. Assoc. Suisse Elect.* volume 32, 1932, pages 605–10.

5. F. Kesselring and F. Koppelmann, *Arch. f. Elektrotech.*, volume 30, 1936, pages 71–108.

6. R. Holm, B. Kirschstein, and F. Koppelmann, *Wiss. veroffent. Siemens Konzern*, volume 13, number 2, 1934, pages 63–86.

7. D. C. Prince J. A. Henley, and W. K. Rankin; L. R. Ludwig and R. H. Nau, AIEE Transactions, volume 59, 1940 (September section), pages 510–22.

8. J. Biermanns, *Bull. Assoc. Suisse Elect.* volume 23, 1932, page 588.

9. H. L. Dryden, *Journal* of the Aeronautical Society, volume 6, 1939, pages 85–9.

10. G. I. Taylor, *Proceedings* of the Royal Society (London), volume 151, 1935, pages 421–78.

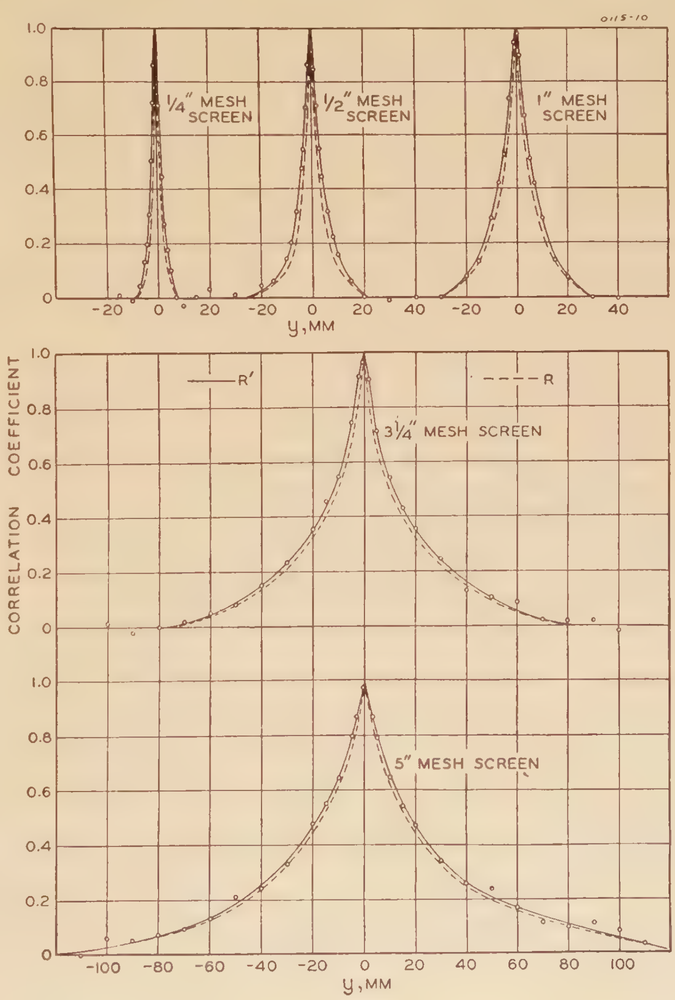


Figure 10. Curves showing variation of correlation coefficient with the cross-stream separation of the hot wires behind screens in wind tunnel, by Dryden

System Stability

F. W. GAY
FELLOW AIEE

Synopsis: That the specter of a major system shutdown is prominent in the thoughts of many operators is evidenced by the 1939 symposium, covering methods of modernization of station-switching facilities, and the 1940 symposium, discussing means of restoring service to systems after a major shutdown. In this paper, system and apparatus performances are studied, during the period between the time allotted for the functioning of the high-speed relay protection, and the point where the system becomes so unstable that a major shutdown occurs. With a view to the further improvement of system operation, the paper studies:

1. Phenomena preceding and during instability;
2. Method of lengthening the period between the fault and instability;
3. A local high-speed back-up relay scheme;
4. Means of automatically and quickly stabilizing an unstable system; and
5. In case all of the above fail, progressive isolation of the system by zones selected by degree of low voltage.

THE length of time to reach the critical period of instability for severe types of faults, that is, a three-phase short circuit near a generating center, is relatively short and the three major phenomena which come into play within a few seconds, following persistent low voltage, are as follows:

1. Machines, which have demonstrated in normal operation that their overspeed trip will not operate following the throwing off of full load, have tripped off on overspeed in three to four seconds upon the occurrence of very low voltage. This appears to be due to the combination of high speed, following loss of voltage and hence load, hunting between machines, and abnormal mechanical vibrations produced by the electrical disturbance. A variation in the setting of overspeed trips may be a contributing cause, that is, machines with fast operating governors are speeded up (motorized) by machines with poor speed control. In rare instances, a turbine will trip almost instantly upon the occurrence of an electrical disturbance, apparently indicating that severe mechanical vibration, as a result of this disturbance, is the sole cause.

2. Modern pulverized fuel and oil-fed boilers require a continuous supply of pulverized fuel or oil and air to maintain the flame. Low voltage, persisting for more than a few seconds is very liable to upset the carefully balanced supply of fuel and air and to result in flame extinguishment. The boiler must then be restarted by hand to avoid a possible explosion. Temporary loss of steaming capacity results. Low voltage, persisting a still longer time, may cause circulating pumps and other vital auxiliaries to fail.

3. Generating stations, or even individual machines, may pull out of step and overspeed, resulting in heavy crosscurrents between generators and a further drop in the already low voltage.

Paper 41-49, recommended by the AIEE committee on power generation and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 19, 1940; made available for preprinting December 11, 1940.

F. W. GAY is assistant engineer for the Public Service Electric and Gas Company, Newark, N. J.

1. For all numbered references, see list at end of paper.

Relief from the above conditions may be had as follows:

1. It is believed that a major portion of all generators on a system will be found to have overspeed trips which may have their trip latches forced back into position when running at speeds well over normal. On two modern machines, turning at 3,600 rpm and having overspeed latches, it was found possible to force back the overspeed latch which tripped at 110 per cent upon a reduction to 105.5 per cent and 103 per cent speed respectively. It should be possible, on most machines, to force back the overspeed trip and automatically return the machine to governor operation within a fraction of a minute after the overspeed latch has tripped. On many 3,600-rpm machines, the manufacturer requires that the turbine not be run at speed without steam flow for much more than 60 seconds.

2. Where switching facilities permit, essential auxiliaries may have their transformer circuits closely connected to one of the generators which may be tripped from the bus during periods of persistent low voltage, while other parallel sources of auxiliary power are simultaneously disconnected so that this generator will automatically become a house generator during the period of persistent low voltage. Essential auxiliary electric motors, serving powdered fuel boilers, should be of ample size and of high pull-out torque. Such motors should be capable of maintaining satisfactory operation down to 60 per cent voltage. An alternate method is to provide relays operating to clear the station bus after low voltage (below 60 per cent normal) has persisted for several seconds. Clearing a station bus may involve resynchronizing after the disturbance has passed and in such a case may involve a temporary loss of load. Auxiliary power transformers must be so connected that this load is not dropped by the automatic withdrawal from service of any single bus.

3. It is becoming generally recognized that, if low voltage persists on a system for much more than two seconds, it is necessary to split up the system into a number of parts so that trouble on one part of the system will not involve the others. This splitting up of a system leads to certain consequences which must be cared for by the operation of the system continuously in preparation for such a split-up; otherwise, some of the parts will have an excess of generating capacity while other parts will be deficient in generating capacity. That particular section of the system, on which the disturbance originated, may be short of generator capacity following the disturbance. It may, therefore, be necessary to drop load temporarily, either manually or automatically. Such reduction in load can probably best be accomplished by automatically reversing the normal function of feeder-voltage regulators and load-ratio control transformers so that, with a reduction of frequency below approximately 58 cycles, there will be a reduction in service voltage to the limit of this regulating equipment's capacity to buck down voltage. This low voltage will be maintained until normal frequency is closely approached.

Whenever a careful study is made following a system disturbance, it is found that communication facilities, which are adequate for normal operation, are inadequate to permit quick restoration of service following the disturbance. It is believed that eventually it may be necessary to install an entirely different type of communication system if it is desired to handle emergencies efficiently. One such system is suggested as follows:

The head operator at the time of the disturbance shall act as a broadcaster giving orders only, and his broadcast shall be audible to all parties who may have an interest in the orders given. His lieutenants will receive information from the field and set up this information in the form of a load dispatcher's board so that the head operator can visually note the actual instant condition of the system. The head operator's orders will carry to every generating station and switching station operator simultaneously and will include, at least, the turbine room operator, the boiler room operator, and the pump room operator in the generating stations so that each of these men will instantly know when their equipment is, or is about to be called on for increased effort. Any company executive or engineer can be plugged into this circuit and can follow the course of the trouble and the restoration of normal conditions.

Twenty important generators in the Public Service Electric and Gas Company system are, or soon will be, equipped with field adjusters. These field adjusters are inoperative during normal conditions, allowing machine-field strengths to be maintained by hand operation at or above stable values, and allowing reactive volt-amperes as well as watts to be allocated by the load dispatcher. Upon the occurrence of low voltage from any cause, these field adjusters operate instantly to add approximately one-third of normal field current to the field of each generator. Upon the return of normal conditions, the fields are automatically returned to their predisturbance value. The amount

of field current added to each generator is chosen so that no injury should result to any field, even if the high-field current is maintained for many minutes. An alarm warns the operator of high-field current and a volt-ampere (ohm) chart indicates meter readings which must not be exceeded.

Persistent low voltage may so reduce the pull-out torque of a generator that it is unable to transmit to the connected low-voltage system the entire output of its connected turbine which is being supplied with a full quota of steam. The unit will speed up until the governor reduces the steam supply to balance the reduced load and the generator will then continue to run out of step as an asynchronous generator. If the unit is equipped with a field adjuster, it should not trip on overspeed.

The Public Service Electric and Gas Company are equipping five turbine-generators with resynchronizing governors which it is hoped, will overcome this difficulty. Associated with each of these governors is an out-of-step relay. This relay determines an out-of-step condition by reason of the simultaneous occurrence of heavy current and pulsating kilowatts. Upon the occurrence of such phenomena, the relays proceed to close the steam valve and this closing operation continues until the out-of-step relay determines that the generator has resynchronized. (This relay does not alter the setting of the governor, but closes the steam valve against the governor.) When the relay determines that the generator has resynchronized, it returns the unit to the governor by backing off slowly so that the rate of steam supply is changed relatively slowly.

The amount of time used to reload the turbine is proportional to the amount of time taken to resynchronize, that is, the rate of change of load is constant.

Instability is a function of voltage loss. It follows quickly on the heels of a severe voltage drop and more slowly for lesser voltage drops. The following is Mr. Dean's conclusion as stated at last winter's convention, and is a good summation of experience in this respect:

"It is interesting to note that the index upon which the necessity for emergency switching turns is the voltmeter reading. It has been found from experience that under fault condition, the behavior of current indicating devices is often so erratic as to make them undependable *and that persisting low voltage is about the only reliable criterion.*"

Figures 1 and 2 illustrate a suggested method of back-up relaying for a utility system, based entirely on low voltage. In figure 1, curve T shows the characteristics of a simple timing relay which operates to close its trip contacts for a voltage on any phase to ground below approximately 60 per cent of normal and its associated timer closes the trip contacts after an elapsed time of 32 cycles.

Curves A and B show the characteristics of timing relays which comprise a voltage element on each phase, operating to close the contacts of a timing element on that phase, for phase-to-ground voltage on any phase below a desired minimum. The timing element comprises a watt-hour meter and a rectifier operating across a resistance to normally charge a battery through this watt-hour meter.

A battery, allocated to each phase, is continuously charged from phase-to-ground voltage on that phase through a step-down transformer and full-wave rectifier. A watt-hour meter in this battery charging circuit is connected to operate in reverse for normal charging. A high-speed register on this watt-hour meter turns in reverse against a stop. For phase-to-ground voltages below a desired critical value, the battery discharges through the resistor and at a rate proportional to the drop in voltage below the desired critical value. During the battery-discharge period, the watt-hour meter turns its high-speed register to close the tripping contacts. The rate of closure is proportional to the drop in voltage below the desired critical value.

The multitrip relay opens the main battery-discharge circuit through the potentiometer resistance of the timing relay and the timing relay slowly resets. This circuit is also held open by the voltage element that operates the timing element described above. The reclosing of this circuit follows the reclosing of the multitrip relay only after the re-energizing of the cleared circuit.

For a meter adjusted according to curve A, the transformer and resistance taps are chosen so that the battery is discharging for phase-to-ground voltages below 40 per cent of normal and, when adjusted according to curve B, the battery is discharging for voltages below 80 per cent of normal.

A suggested use of these relays is illustrated in figure 2 wherein a system, Y, is connected to the NY bus of station N, having short-circuit capacity on the bus NY of 1,000,000 kva with system Y alone connected; that is, a per-unit reactance for system Y of ten per cent, based on 100,000-kva unit. The bus NY is shown connected to the red and blue busses of station N by transformers T-5 and T-6. These transformers are of the double-wound secondary type and have an equivalent primary negative reactance of minus 15 per cent (per unit of 100,000 kva) and an individual secondary reactance of plus 60 per cent. One of the secondaries of each transformer is shown connected to the red N bus and the other connected to the blue N bus. Additional stations O, P, and Q are shown with N and each have a red and blue bus. Load on each red bus is carried by transformers such as NRT, ORT, etc., each feeding a low-voltage load bus, L-1, and load on each blue bus is carried by trans-

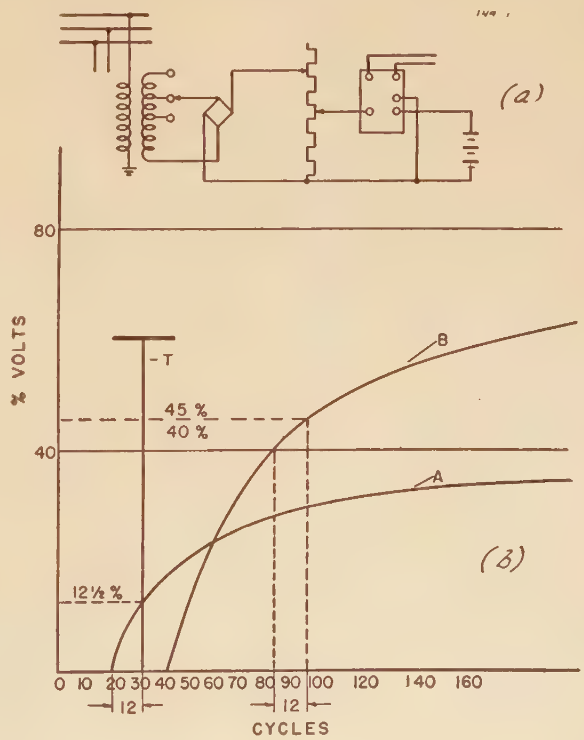


Figure 1a. Diagram of timing element in suggested relay scheme b. voltage-time curves

Curve A—Timing element set for 20 cycles (maximum closing speed); range adjusted for operation between zero and 40 per cent volts

Curve B—Timing element set for 40 cycles (maximum closing speed); range adjusted for operation between zero and 80 per cent volts

formers such as *NBT*, *OBT*, etc., each feeding a low-voltage load bus, *L*-2. The *L*-1 bus is shown connected to the red bus of each station through a transformer having a per-unit reactance of 20 per cent and to a tie bus in common with *L*-2 through 20 per cent reactors. The *L*-2 low-voltage bus is similarly connected to the blue bus and the tie bus. At stations *P* and *Q* two 100,000-kw generators (125,000 kva) are shown, each connected to the red and blue bus through a two-winding secondary transformer having equivalent negative primary reactance of 15 per cent, and a secondary winding reactance of 60 per cent for each winding alone. One secondary of each transformer is shown connected to the red bus and the other secondary to the blue bus. The arrangement shown is identical at station *P* and at station *Q*.

If, now, it is assumed that a three-phase short circuit occurs on the terminals of the power transformer connecting the high-voltage blue bus to the *L*-2 low-voltage bus at station *P* (short-circuit *X*, figure 2) and further, that the relays on this short-circuited transformer bank fail to operate, then a three-phase short circuit will remain at *X* on the blue bus *P* until the *PBT* transformer breaker is opened. (This fault will also remain on low-voltage load bus *L*-2.) The short circuit will, in effect, be a bus short circuit. To this bus, as well as to all other busses, is shown connected a relay of the *A* type, figure 1. With zero voltage on the blue bus at station *P*, the type *A* relay battery will discharge its maximum current through the current coils of the wattmeter-relay element and the high-speed register will turn at maximum speed to close the tripping contacts. As shown on curve *A*, figure 1, these contacts will be closed at approximately 20 cycles after the short circuit occurs, and since the high-voltage breaker on the transformer feeding the *L*-2 low-voltage bus has not operated, all high-voltage breakers connected to the *P* bus will be tripped and the *P* blue bus will be killed within the next 12 cycles. If pilot wire or carrier current is available, the breakers at both ends of lines leaving the blue bus at station *P* may and should be tripped. Voltage-timing relays *T* are shown for the reactor tie busses connecting load busses *L*-1 and *L*-2 at each station. With a short circuit at *X*, figure 2, as shown, the voltage on the tie-reactor busses at stations *N*, *O*, *P*, and *Q* may be less than 60 per cent normal and, if so, these relays start functioning to trip the *L*-1 reactor breakers so that the red and blue busses at stations *N*, *O*, *P*, and *Q* may not be connected through the low-voltage reactor busses. With a short circuit at *X*, as shown, the blue bus at *P* will be removed from circuit before relays *T* operate and only the *T* relay at station *P* will function, due to the fault on its connected transformer bank.

A study of curve *A* will show that, for the arrangement shown, if blue busses at stations *O* and *Q* have a voltage in excess of 12.5 per cent of normal, there will be no danger of the type *A* relays on these busses beating the type *A* relays on the *P* bus. (See dotted lines in figure 1.) With the arrangement as shown, the voltage on the red bus during the short at

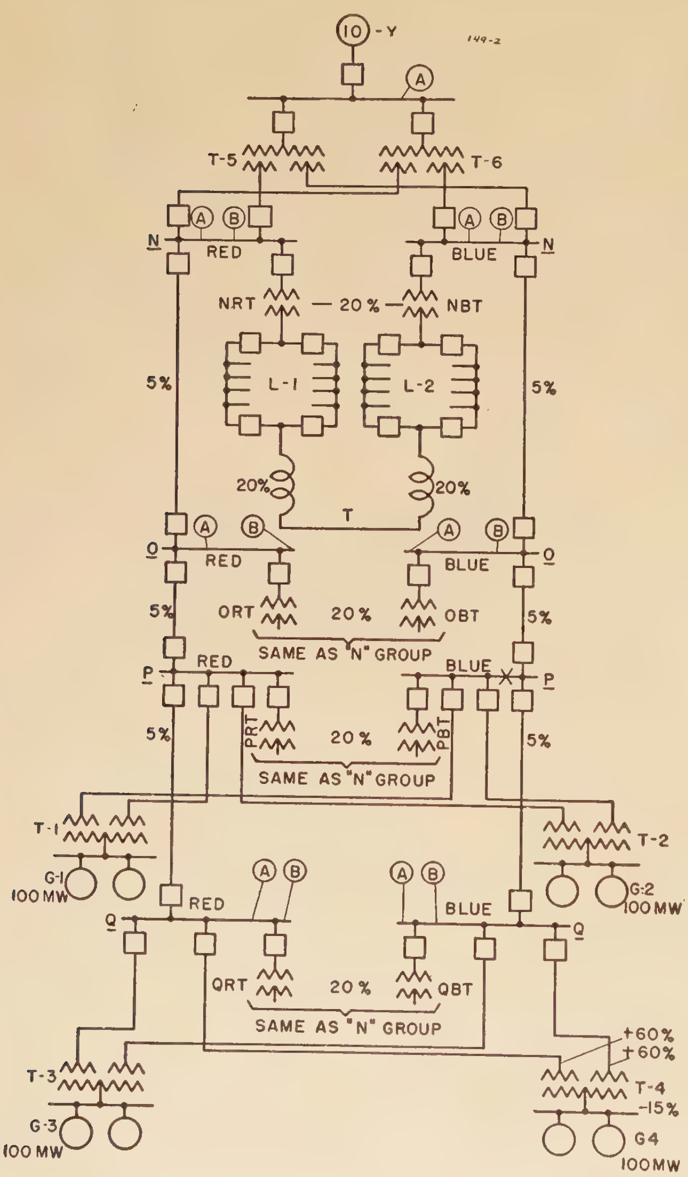


Figure 2. System layout

Employing three-winding transformers, each having a per-unit through impedance of 15 per cent (100,000-kva unit) and minus 15 per cent equivalent negative primary impedance, i.e., 45 per cent impedance through one high-voltage winding

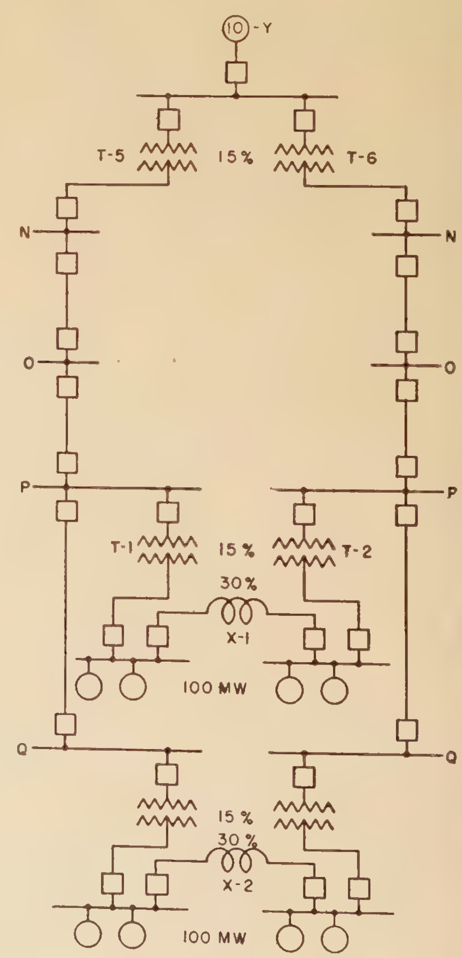


Figure 3. System layout

Similar to figure 2 but employing two-winding transformers each having a per-unit through impedance of 15 per cent (100,000-kva unit)

X will be over 100 per cent and on the blue bus at stations O and Q there will be a safe margin of voltage over the 12.5 per cent minimum required. The only load that will be lost will be that of the L-2 bus, connected to the faulted transformer bank. This bus may be re-energized immediately through the reactor circuits. A short circuit on any high-voltage bus should be cleared by this back-up relay scheme without danger of killing any adjacent bus. Curves A and B show that, as voltages, during a fault, become higher, the selectivity improves.

The use of relays with a B setting are required for protection against persistent low voltage originating outside the high-voltage circuit of the system under consideration as, for instance, trouble on the interconnected system Y. If the trouble is sufficiently serious to endanger service on the red and blue bus, the B relays at station N will function and are connected to trip the oil-circuit breakers of transformers T-5 and T-6. Again, if the generators or turbines at, for instance, station Q, should be in serious trouble, the B relays at station Q will function to open the output breakers of these generators.

No brief is held for the operating time used in this discussion except that the operating times closely approach the minimum. Longer times will obviously give greater selectivity.

The advantages of a relay scheme similar to the above are as follows:

1. Any generating station bus which has a voltage on it sufficiently low to cause hazard to auxiliary power-station equipment will be removed from service by the back-up relays in a period so short that the functioning of the auxiliary power equipment will not be seriously disturbed.

Note: With this system, auxiliary power transformers must be connected to generator circuits before these circuits reach the station busses, since station busses may be automatically killed in case of a bus fault.

2. A bus at any generating station will be removed from service so quickly that there will be no danger of unloading generators with consequent tripping of overspeed relays and temporary loss of capacity on the system.

3. The low voltage will exist for so short a time that system stability will not be in danger.

Figure 3 differs from figure 2, described above, in showing a more usual transformer arrangement at generating stations P and Q and interconnecting station N. All load circuits L-1 and L-2 are omitted in figure 3 in the interest of simplicity, as are the red and blue designations. A 100,000-kw (0.8 power factor) generator is shown connected directly to the primary of each of two 125,000-kva transformer banks, T-1, T-2, T-3, and T-4 and the transformer primaries at each station, as at P and Q, are shown connected together through reactors having a per-unit value of 30 per cent (100,000-kva unit). The six transformers, T-1, T-2, T-3, T-4, T-5, and T-6 in figure 2 and in figure 3, are shown to have a straight through reactance to balanced loads of 15 per cent; however, the two-winding transformers shown in figure 2 have an equivalent negative primary reactance of minus 15 per cent and a positive reactance of 60 per cent for each of the high-voltage windings singly so that the reactance from any individual generator to either the red or the blue bus will be 45 per cent for the transformer and, adding the generator subtransient reactance of 10 per cent, 55 per cent total to an individual bus. For balanced loading, the reactance from an individual generator to both busses will be 15 per cent for the transformer plus 10 per cent for the generator, or a total of 25 per cent, and will be the same for both figures 2 and 3. If, in figures 2 and 3, a badly unbalanced condition is considered, that is, 60 per cent load on each of the blue busses against 40 per cent load on each of the red busses as shown, and the generators are loaded to capacity and there is no interconnection load, we find that the total load on the blue bus will be 240 mw and 180 mvar (300 mva) and on the red bus 160 mw and 120 mvar (200 mva). Each transformer shown in figure 2 will be equally loaded, that is, it will have 125 mva on its primary winding and 75 mva on one secondary winding and 50 mva on the other secondary winding. The total loss in each transformer in figure 2 will be approximately 102 per cent of normal, indicating that a small amount of additional copper will have to be added for both high-voltage windings above that required for a balanced load condition. In contrast, in figure 3 it is seen that the two transformers connected to the blue bus must take the maximum load, in both their primary and secondary windings, that is, the transformers will carry 120 per cent of the normal generator rating and will have 144 per cent load loss. The transformers in figure 3 must, therefore, have a continuous-carrying capacity of 150,000 kva per bank. In other words, the single-winding secondary transformers, shown in figure 3, must be something more than 15 per cent larger than the double-winding secondary transformers shown in figure 2. Furthermore, with the instantaneous reactances given, should there be a fault at X, as shown on the blue bus for station P, the voltage of the generator connected to transformer T-2 will be approximately 82 per cent at the instant of fault, while the corresponding voltage at generator terminals in figure 3 will be approximately 63 per cent.

Assuming that all generators are of the modern type, equipped with field adjusters and having a sufficiently high-exciter ceiling voltage to maintain approximately 200,000 kva per generator through the fault, the sustained voltage, with the arrangement shown in figure 2, will be approximately 90 per cent for each of the generators connected to the red and blue bus in station P, and 48 per cent for the generator connected to the blue bus in the arrangement shown in figure 3. Furthermore, since the blue bus at station P is short-circuited, synchronizing power for generator G-2 is through reactor X-1 to generator G-1 only. It is obvious that generator G-2, shown in figure 3, will fall out of step and run above synchronism in the assumed case of failure, that is, relays fail to clear the faulted transformer bank PBT, feeding load bus L-2 so that the blue bus at station P remains short-circuited.

In figure 2, both generators G-1 and G-2 are equally affected by the fault at X and also both generators are connected to the red bus and will not pull out with respect to each other or be unloaded and run over speed. Furthermore, the voltage of the red bus will be over 100 per cent of normal and there will be a powerful synchronizing tie to generator G-3 and G-4 at station Q over the line connecting the red busses at these two stations. Phantom current will flow through the line connecting the blue bus at station P with the blue bus at station Q. This current will flow due to the mutual inductance between the two high-voltage windings of the transformers T-1 and T-2. This phantom current will flow directly through the faulted blue bus but not into the fault and will serve to maintain a low impedance between generators G-1 and G-2 on the one hand, and generators G-3 and G-4 on the other hand, and between the individual generators G-1 and G-2 and between the individual generators G-3 and G-4.

Several years ago, a small model system was set up to determine if the impedance between two machines connected by two parallel transmission circuits could be maintained substantially constant while either of the connecting circuits were simultaneously grounded on all three phases. It was found that, with a relatively enormous equivalent nega-

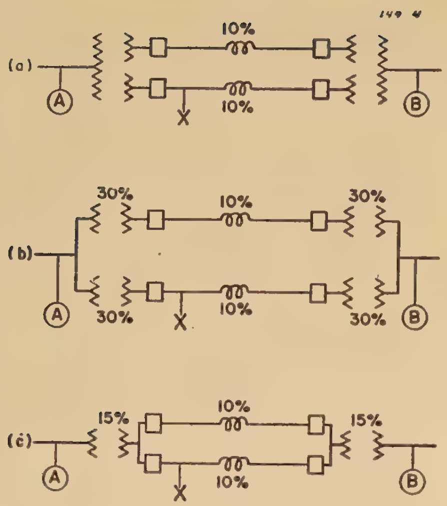


Figure 4

(a)—Simple two-circuit transmission system employing terminal transformers, each having two separately insulated high-voltage windings. Each transmission circuit served by an individual high-voltage winding at each end

(b)—Same as (a) above but each transmission circuit having its own transformer at each end

(c)—Same as (a) above but a single transformer at either end serving both transmission circuits at that end

tive primary impedance in the transformers at both ends of the lines, either connecting line could be short-circuited and the voltage on the nonshort-circuited line would be instantly doubled. The power would flow over the nonfaulted line at double voltage and a phantom power current of substantially equal value flowed over the short-circuited line but did not enter the short circuit.

As the equivalent primary negative impedance of the transformers at both ends of a dual circuit transmission is reduced by design from a relatively enormous value to zero, the effect of a single-line short circuit on the through impedance will be found to change, having substantially no effect for very high negative and double the impedance for no negative.

The value of equivalent-negative primary impedance in reducing fault currents has been well covered in the technical press but the value of such negative impedance in maintaining a stable system seems to have been neglected.

In order to better assure the reliability of large capacity, closely coupled systems, it is believed that operators and manufacturers must find some solution to the factors causing instability outlined in this paper. While the experiences described cover those of one system only and the remedies suggested have had very limited or no field trial, it is hoped that after further development they will prove of substantial value.

Appendix

A two-circuit transmission system was set up on the circuit analyzer to determine the characteristics of a double-wound high-voltage transformer bank having various amounts of equivalent primary negative impedance.

Figure 4 (*a*) is a one-line diagram showing a hypothetical system *A* having infinite capacity connected to a like system *B* by a transmission circuit comprising two transmission lines, each having ten per cent reactance (100,000-kva unit) and being serviced by a transformer at each end, having a single low-voltage winding and two high-voltage windings. Each transmission line is served at each end by an individual high-voltage winding.

Figure 4 (*b*) shows a somewhat similar circuit connecting the two systems *A* and *B*. In this arrangement individual transformers are used in each transmission circuit, each transformer having twice the through impedance of the transformer shown in (*a*) above, that is 30 per cent.

Figure 4 (*c*) shows the same two systems, *A* and *B*, connected through individual transformers to the same two circuits. It is obvious that in normal operation, the performance of the three systems, *a*, *b*, and *c* will be identical, since the through reactances are the same and resistances are neglected.

If a three-phase fault is applied at *X* in

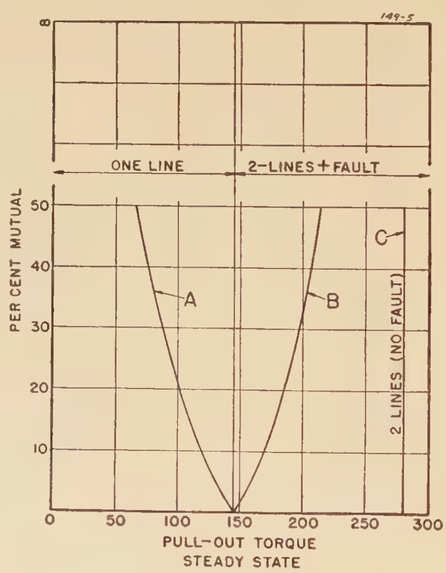


Figure 5. Steady-state pull-out torque of system shown in figure 4a

(a)—Variation of steady-state pull-out torque with per cent mutual for a single line in circuit, i.e., the faulted line cleared at both ends

(b)—Variation of steady-state pull-out torque with per cent mutual for two-line operation and a three-phase fault on one line at X

(c)—Variation of steady-state pull-out torque with per ce.t mutual for two-line operation

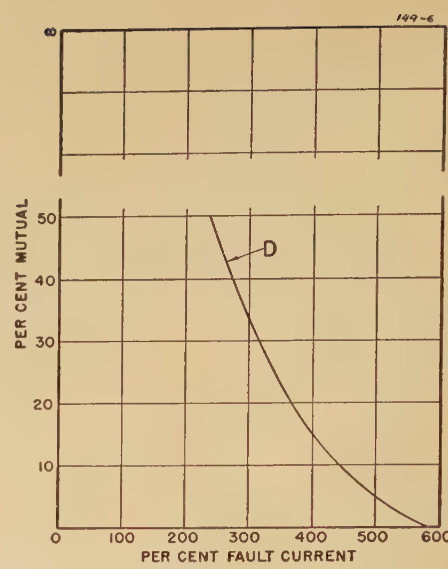


Figure 6. Variation of fault current with per cent mutual

each of these systems, it will not be possible to transmit any power between the system *A* and the system *B* with the arrangement shown at (*c*), while with the arrangement (*b*) the power transmitted between system *A* and system *B*, with the three-phase fault existing, will be only one-half the amount that may be transmitted without the fault. (The current flowing from systems *A* and *B* into the fault is of no consequence since these systems are assumed to have infinite capacity.)

In arrangement (*a*), if the equivalent negative primary impedance (per cent mutual) in the transformers is a maximum by design, then the current that will flow into fault *X* will be negligible, and the transmitting characteristics of the circuit shown in (*a*) will be the same whether the three-phase fault at *X* is present or clear. If the fault is on, the voltage on the nonfaulted line will be 200 per cent. The current flowing in the faulted line will be identical to that flowing in the unfaulted line. This current is called a phantom current and is induced in the faulted line by the mutual impedance in the transformer circuits. As the mutual impedance is diminished, the volts on the sound line during the fault will diminish and the phantom current in the faulted line diminishes.

Figure 5 shows the characteristics of circuit (*a*). The steady state pull-out torque in per-unit (100,000-kw unit) will be approximately 280 per cent, with both lines in circuit and without a fault. This pull-out torque will be a constant, regardless of the amount of equivalent primary negative impedance (per cent mutual) built into the terminal transformers, so long as there is no fault on either transmission circuit. If however, there is a fault on one circuit, the steady-state pull-out torque is shown by curve *B*. This pull-out torque will reduce with a reduction in equivalent negative primary impedance and for zero negative the circuit is the equivalent of (*b*), and the steady state pull-out torque will, of course, be one-half of what it is with an unfaulted line. If now the faulted circuit is opened at both ends to clear the fault, the transmission will be left with a single circuit and

The Water-Cooled Steel-Tank Rectifier Corrosion Problem

EMIL J. REMSCHEID
MEMBER AIEE

Synopsis: The first mercury-arc rectifiers utilized glass tubes and consequently the physical size and electrical capacity was limited. The efforts to increase the available output led to the development of water-cooled steel-tank vacuum chambers after many years of research and the solution of many problems. This paper is primarily concerned with the solution of the problem presented by corrosion. Corrosion is essentially the returning of a metal to its original state and the problem consists in finding a means to retard the return sufficiently so that corrosion will not be a limiting factor in the life of rectifiers.

Analysis of the problem indicates that pitting corrosion causes the greater damage and is largely a function of the character and condition of the metal, the quantity of electricity passing, and also that it is self-propagative. The rate of corrosion is affected by the temperature of the cooling water, the chemical constituency of the water, and potential differences between points on the surface of the rectifier tank.

The first efforts in the solution of the corrosion problems were directed toward finding a protective coating to isolate the steel tank from the cooling water. Various paints, varnishes and lacquers, and enamels were investigated, as well as sprayed metal, but were not found satisfactory. Chemical treatment of the water was then investigated and sodium chromate found to give excellent results. The action of this chemical is reviewed and both laboratory and field evidence of its effectiveness submitted, followed by a discussion of the various factors to be considered in the application of this chemical to prevent corrosion.

Introduction

WITH few exceptions, all machines for the generation and conversion of electrical energy have been mechanical in nature. During the early part of the present century, Cooper-Hewitt and Steinmetz presented to the electrical world a conversion unit for transforming alternating current to direct current which was nonmechanical, but electronic in nature. This conversion unit known to us as the glass-bulb mercury-arc rectifier, has since its introduction won wide acclaim as an efficient, practical converter. Because of the fragility of glass, the physical size and current rating of the mercury-in-glass rectifier has been essentially limited. The desirable features of this particular type of converter are as follows:

(*a*). High operating efficiency

(*b*). Silent operation

(*c*). Absence of moving parts

(*d*). Comparatively long life

Studies were soon begun to increase the current rating, operating potential, and naturally its physical size. As it was impractical to increase the physical size of the mercury-in-glass rectifiers, a substitute for glass was sought. This investigation which was carried on by several groups, both in the United States and abroad, resulted in the adoption of the steel-tank vacuum chamber. Subsequent investigations indicated that by surrounding the steel vacuum chamber with a water jacket, the heat losses[1] could be effectively removed and the rating of the rectifier considerably increased. This transition from the glass to steel vacuum chamber and the increase in rectifier rating required several years of research and necessitated the solution of many problems before this new rectifier was available for service in the field. It is the purpose of this paper to explain the steps taken to overcome one of these problems, namely the corrosion problem, which became evident during the early days of the water-cooled steel-tank rectifier field performance. While this subject does not pertain to the phenomena of rectification, nevertheless, its immediate solution was necessary in order to give the assurance that the life of the water-cooled steel tank rectifier would not be limited by corrosion. This assurance would make its future manufacture and application economically justifiable.

Paper 41-25, recommended by the AIEE committee on electrical machinery, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted March 4, 1940; made available for preprinting December 3, 1940.

Emil J. Remscheid is employed in the power rectifier engineering department of the General Electric Company, Schenectady, N. Y.

1. For all numbered references, see list at end of paper.

The Corrosion Problem

Water when available in sufficient quantities is one of the most practical and economical mediums for controlling the temperature of machines. Likewise, iron is one of the most practical and economical metals for the fabrication of machines.

The application of water in contact with iron presents to the manufacturer and operator of electrical apparatus, the so-called "corrosion problem." This problem presents itself in varying degrees, occasionally of no consequence, and then again if not retarded, considerable damage results. This damage may appear as loss of good will, interrupted service, or expensive repairs. The performance or the life of electrical or mechanical apparatus of the present day should not be determined by the corroding away of the water-cooled iron parts.

Because of the many different theories regarding its nature, corrosion is generally studied from an academic point of view. When one studies the many possible causes for the corrosion of iron, one can readily appreciate why the early students of the corrosion problem, asked themselves, why ferrous metals survive corrosion at all.

Corrosion of metals is essentially the reverse of smelting, or in other words, corrosion is the returning of a metal to its original ore state. As corrosion in the theoretical sense cannot be entirely stopped, nevertheless, we must find means to retard it sufficiently so that corrosion will in no way be a factor to impair the performance or limit the expected life of apparatus, especially where water is used as a coolant.

The temperature of steel-tank rectifiers of early manufacture were controlled by tap water cooling, using whatever water was available for the purpose. In locations where water from city mains was not available, wells were provided near the station. As the quantity of water available was the criterion rather than the quality, many of the waters corrosive in nature were used as a coolant. The more corrosive waters attacked the iron parts of the rectifier and subsequently advanced stages of corrosion

---

with this single circuit, the one-line steady state pull-out torque will vary inversely as the negative impedance (per cent mutual), diminishing with an increase in such impedance in accordance with curve A. The current in the fault X will vary with equivalent primary negative impedance having approximately 580 per cent value for zero negative impedance (per cent mutual), and diminishing along the curve D to have a zero value for an infinite negative impedance (figure 6).

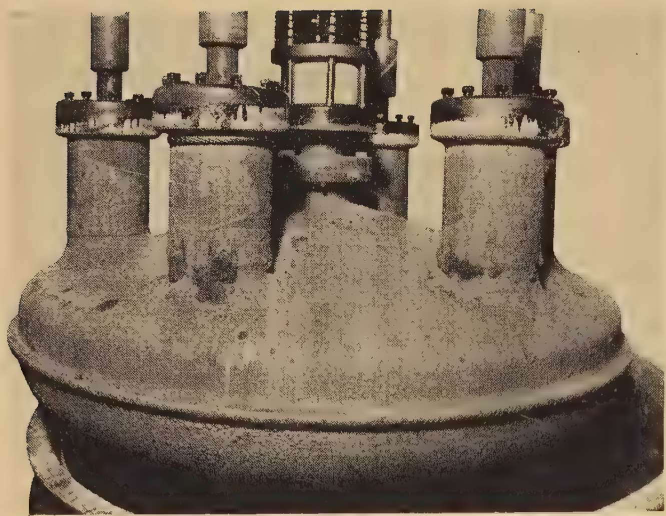


Figure 1. Tubercles on mercury-arc-rectifier vacuum chamber

were noted, some instances resulting in vacuum leaks in the rectifier or water leaks in the water jacket.

The Corrosion Study

Examination of the corroded parts of various rectifiers indicated that pitting corrosion rather than the so-called general corrosion was causing the greater damage. In "general corrosion" the anodic and cathodic areas which characterize all corrosion attack by water on iron are evenly distributed and of such fine grain, so to speak, that the net attack is fairly uniform and so slow as to be unimportant. This effect is largely a function of the character and condition of the metal. No way is known to insure that corrosion attack shall be confined to this type. "Pitting corrosion" occurs when positive anodic areas are set up surrounded by relatively large cathodic areas. This may result from patches of mill scale or other foreign matter or from inhomogeneity of the metal, as at welded junctions. It is the usual situation in fabricated structures since anodic areas are essentially areas of oxygen starvation. The resultant pitting is self-promoting: The condition once established tends to become worse. Figure 1 shows the presence of tubercles of iron oxide resulting primarily from pitting corrosion. These tubercles are small mounds which grow in size in proportion to the quantity of electricity passing between the covered portion acting as anode and the surrounding metallic surface acting as cathode, and are generally found at welded junctions, breaks in mill scale or at a point where a foreign substance is attached to the iron. From within the tubercle or pit anodically produced iron salts diffusing outward meet a relatively alkaline water from the cathodic area whereby the iron is precipitated forming mounds of black magnetic iron oxide, which further obstruct the access of oxygen. Being loose and not adherent, they do not constitute a protective film. Deposits of this nature, when not removed and the pits repaired or thoroughly cleaned, ultimately cause perforation of the water jacket. Tubercles shown in figure 1, occurred at the hottest point and on a welded surface. Figure 2 shows the surface of a rectifier water jacket before cleaning. Many tubercles and much water sediment is evident, with a fertile field for corrosion. Figure 3 shows the cleaned surface, with the pits in the iron jacket plainly visible. It is readily seen that such disintegration if allowed to continue will reduce the active life of apparatus. The application of sodium chromate even in this advanced stage will stop corrosion and make corrosion no longer the limiting factor of the machine's life. This preliminary study taking into consideration the several variables all conducive to corrosion, placed the rectifier corrosion problem in a category of its own. These variables may be enumerated as follows:

The rectifier water temperatures are variable, often ranging from tap water temperature to boiling water temperature.

The waters in different localities also differ in chemical composition.

During operation the steel tank rectifier has inherent differences in potential between points on its surface.

The rate at which corrosion occurs, is greatly increased with increase in temperature. This is due mainly to the fact that both the electrical conductivity of an electrolyte and the rate of chemical action increase with temperature. It is for this reason that water-cooled parts of rectifiers operating in excess of 50 degrees centigrade corrode at a considerably higher rate than those operating at lower temperatures.

It is of interest to note the differences in chemical constituents of the various waters used as rectifier coolants throughout the United States. These waters are classed as lake waters, river waters, mountain spring waters, and local well waters. The following table shows the extremes, in parts per million (ppm) of the constituents in these various waters:

	Maximum	Minimum
Total hardness ($CaCO_3$)	370	3
Total dissolved solids	353	19
Silicon (Si)	39	1.6
Iron (Fe)	1.4	0
Calcium (Ca)	107	0.8
Magnesium (Mg)	25	0.2
Sodium (Na) Potassium (K)	74	1.2
Bicarbonate (HCO_3)	289	7.3
Sulphate (SO_4)	120	1.7
Chloride (Cl)	44	0.7
Nitrate (NO_3)	25	0

The excess of some of the constituents listed in the above table are harmless, while the excess and combination of others provide fertile grounds for corrosion.

The presence of calcium carbonate is nearly universal. Where it is not associated with an excess of free carbonic acid it tends to precipitate along with the rust on iron surfaces forming a dense scale which resists further corrosive attack. In fortunate cases, the accumulation of this scale is so slow that it does not cause troublesome interference with heat transfer. Where, on the other hand, an excess of free carbonic acid is present deposition of calcium carbonate is prevented and the water becomes "aggressive" toward iron.

The first step in the search for a remedy of the rectifier cooling system-corrosion problem was naturally to find a protective coating which would perfectly isolate the iron parts of the rectifier from the water of the cooling system and thus prevent corrosion.[2] Asphaltum, metallic and metallic oxide paints recommended for their corrosive-preventive merits were studied. Varnishes and various lacquers were investigated. The corrosion-resisting properties of sprayed molten metals and their combinations were likewise investigated. Both air drying and baked vitreous enamels applied to iron surfaces were given vigorous tests.

The tests revealed that the binder in many of the air-drying applications would dissolve in warm water, while others would dry sufficiently porous to permit corrosion to develop.

It was also found that sprayed metal

Figure 2. Tubercles on mercury-arc-rectifier water jacket

Figure 3. Electrolytic corrosion on mercury-arc-rectifier water jacket

would not make a sufficiently homogeneous surface to prevent water from reaching the iron. Similarly it was discovered that metals near the alkali end of the electromotive-force series would not long withstand the solvent action of the water. Therefore the effective life of metals of this nature would depend on the thickness of the coating.

Enameled surfaces in iron were found not sufficiently homogeneous to retard electrolytic corrosion. The application of vitreous enamels in preventing corrosion of rectifier surfaces was found very detrimental because any microscopic hole or crack in the enamel surface would take the total electrolytic current for the section and thus in a comparatively short time sufficient disintegration would occur to cause a vacuum leak.

Following the negative results of this initial investigation, it was decided to study methods of chemically treating the circulating water. For this test commercial corrosion-preventive liquids, oils, and many miscellaneous chemicals were studied. These were studied at constant and varying temperatures for their general and electrolytic corrosion-retarding qualities.

The study revealed several more or less promising treatments of the water for retarding general corrosion under the operating conditions of power rectifiers, but only one, a soluble chromate, $Na_2CrO_4 10H_2O$, effectively controlled both general corrosion and the intensified action due to electrolysis.

Sodium dichromate $Na_2Cr_2O_7 2H_2O$, is usually used to supply the chromate for a corrosion-inhibiting solution, because this salt is readily obtainable and is of low cost. Many natural waters are sufficiently alkaline to convert this to the chromate. Where this is not the case it is advisable to add the requisite alkali. This does not materially affect the anticorrosive action of the chromate, but may prevent a rapid loss of the chromate from certain unwanted side reactions due to impurities in the water.

As an example of the effectiveness of a sodium chromate-treated coolant, the photograph figure 4 is submitted, showing three iron electrodes, all immersed in their respective containers for 12 days. The electrodes were immersed in separate containers, *A*—the positive electrode of a cell containing Schenectady tap water, *B*—the positive electrode of a cell containing a one-half per cent solution of sodium chromate using Schenectady tap water. A five-volt potential was impressed between the electrodes of the two cells. Electrode *C* was placed in a container of Schenectady tap water, with no potential impressed. Electrode *C* is an example of the so-called general corrosion, a fairly uniform covering of reddish-brown iron oxide. No tubercles or concentrated corrosion is noted on this specimen. Electrode *A* shows the effect of electrolytic disintegration, much of the iron having been removed by the effect of the few milliamperes of current. As a contrast, electrode *B*, which was immersed in a sodium chromate solution shows on microscopic examination no evidence of either the so-called general or concentrated form of electrolytic corrosion. It is interesting to note that by virtue of the relatively high electrical conductivity of the sodium chromate solution, approximately ten times as much current was passed between the electrodes of this cell in comparison with electrodes of the cell containing tap water and electrode *A*. Subsequent tests where the cell current was increased several hundred per cent, indicated that even with this unusual current, the one-half per cent solution of sodium chromate was capable of inhibiting electrolytic corrosion.

This passivating action of the chromate is somewhat complex. Recent research[3] indicates that it is not a simple oxidizing action. Other powerful oxidants such as the permanganates and

Figure 4. Three iron samples after corrosion test

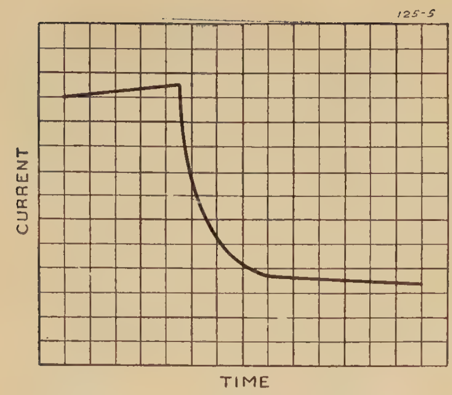


Figure 5. Current characteristic during growth of protective chromium film

hydrogen peroxide produce no such effect. The effectiveness of the protective oxide film produced, appears to be due not only to the simple production of a film of iron oxide but also to the inclusion of chromic oxide in the precipitate or rust formed in the simple corrosion reaction. This so modifies it that a dense and adherent protective film results rather than a loose nonprotective rust or tubercle. Of these factors the inclusion of Cr_2O_3, is probably the most important as the other action is also common to other oxidizing agents which have less or no protective effect.

The growth of the protecting chromate film is an interesting phenomenon, as shown in figure 5. With the deposition current as abscissa and time as ordinate we see what normally occurs in a few seconds or a few minutes, depending upon the chromate concentration and the existing difference in potential. The formation of the film takes place quickly, and then the deposition current which generally is of the nature of a few milliamperes, gradually recedes as the thickness of the film increases. Ultimately, the current reaches a minimum value. Laboratory cell tests made to determine the proper concentration of sodium chromate indicated, as would be expected, electrolytic corrosion at the positive terminal when untreated water is used. By the addition of a small amount of chromate it was noted that the effects of electrolytic corrosion became more pronounced. With each subsequent small increase up to a certain amount, the effects of electrolytic corrosion increased proportionally. When the critical amount was exceeded, it was noted that the evidence of electrolytic corrosion abruptly stopped.

The resistance of chemical solutions varies with their nature, concentration, and temperature, the higher-temperature solutions being the better electrical conductors. The chromate solution of the concentration used as the rectifier coolant is many times the better electrical conductor than is the average tap water. This fact is shown in the curves figure 6, where the electrical conductivity of Schenectady tap water and sodium chromate solution are shown at increasing temperatures. These relative curves show the trend of their respective conductivities as measured with one-sixteenth-inch diameter wire electrodes at a distance of one inch, and with current values approximating those found passing between different parts of the rectifier cooling system. The important consideration of these curves is that ample lengths of insulating coolant conductors must be provided between points of different electrical potential; so that the amount of leakage current will be negligible.

The application of chromate as a corrosion inhibitor is by no means new. Solutions containing chromate have been used for many years in the retarding of the general corrosion of iron.[4] The application of a sodium chromate coolant to specifically retard pitting corrosion in the steel-tank power rectifier, apparently is a new field of service.

The Applications of Sodium Chromate

The laboratory tests revealed that a one-half per cent solution of sodium dichromate was sufficient for the average water used as a rectifier coolant. This strength of solution has been found to be sufficient to inhibit corrosion when the solution is made up of any waters of potable purity. Where waters are available which are of exceptional purity, then it is possible to reduce the percentage of solution. A safe solution percentage can be determined definitely by the electrochemical means, explained below. Naturally the safest solution is made using distilled water, where the absence of foreign chemicals which would tend to react with the sodium dichromate and thus limit its life as a corrosion inhibitor is assured. Solutions made up of potable waters containing an excessive amount of chloride will require the full amount of sodium dichromate in order to obtain the full corrosion protection of the dichromate solution.

Before installing anticorrosive treatment in rectifier cooling systems, it is essential that all metal surfaces be perfectly clean. The coolant is made by adding a sufficient amount of the orange-colored sodium dichromate crystals of technical purity, to the water of the cooling system. A one-half per cent solution requires 4.2 pounds of the crystals to every 100 gallons of cooling water. The crystals are readily dissolved in cold or warm water and as soon as added to the system the coolant should be circulated.

The following method of checking the effectiveness of any given treated water has been found convenient and practical. A sample of the solution is placed in a glass bottle provided with two iron-wire electrodes spaced about one inch apart. Impress approximately five volts d-c potential across the electrodes. Should the solution be weak, a grayish-colored formation or precipitate will become visible within 5 to 30 minutes about the positive electrode, indicating anodic attack which may also be seen on close inspection of the electrode. The solution should then be strengthened and the test again repeated. Should the solution be of sufficient strength to retard corrosion, no precipitate will form around the electrodes. In order to eliminate any possible external influence, it is desirable that all such tests be made at a specific solution temperature maintaining the same size of bottle and dimensions for the electrodes.

Field Experience With Sodium Dichromate

Sodium dichromate has been used as a corrosion inhibitor in the steel-tank power rectifier since 1930. Since this time, all rectifiers in which the inhibitor solution was properly maintained have been free from both the general and concentrated pitting corrosion. Prior to the application of sodium dichromate, the temperature of practically all steel tank rectifiers, was controlled by tap water cooling. At the present time only 12 per cent of the rectifiers have tap-water temperature control, the remaining 88 per cent are provided with recirculating cooling sys-

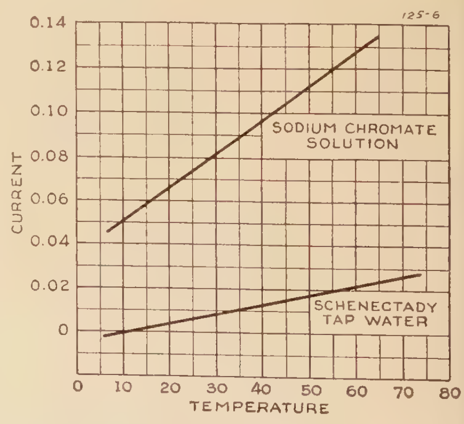


Figure 6. Electrical conductivity versus temperature

tems and treated water. Of the rectifiers originally operating with tap water cooling, approximately 25 per cent have experienced corrosion trouble terminating in vacuum leaks.

The life of a sodium dichromate solution depends upon the amount of make-up water added to the closed circulating system, and also on the chemical nature of the raw water. Our experience indicates that some solutions using mountain waters which are essentially pure, have a life in excess of three years. Well waters which are potable but have a higher impurity content, when made into an inhibiting solution have a life ranging upward from nine months. As already indicated, it has been found that the addition of small amounts of caustic soda (NaOH) to the chromate solution would increase its effective life. The function of the soda is to convert the inhibitor to a neutral chromate. A proportion of 1.5 (NaOH) to 5 ($Na_2Cr_2O_72H_2O$) ordinary crystalline dichromate, is sufficient in most cases. Slightly more (NaOH) than this proportion will do no harm. It has been found desirable to make periodic electrochemical examinations of the efficiency of an inhibiting solution; this can be done monthly or semiannually, depending upon the chemical nature of the water used, and the amount of water added for make-up.

Figure 7 shows the rectifier tank indicated in figure 1, but following the application of sodium dichromate. This rectifier had previously operated on a closed cooling system using untreated water, during which time the carbuncles, some shown in figure 1 had produced the pitting indicated. Following the first 11-month application, no new indications of pitting were evident and the vacuum chamber was in a clean condition as indicated in figure 7. Since this photograph was taken, this rectifier has been operating continually for the past six years without corrosion troubles.

Various Types of Cooling Systems

Sodium dichromate coolant is equally as well adapted to either water-to-water or water-to-air type of temperature regulators. The application of either type depends naturally on the particular installation. Locations such as the railway subways, where a comparatively high ambient temperature prevails at all times, the water-to-water temperature regulator is the most satisfactory. In such cases where the prevailing ambient temperature is slightly below the operating temperature of the rectifier, water-to-air temperature regulators can be applied.

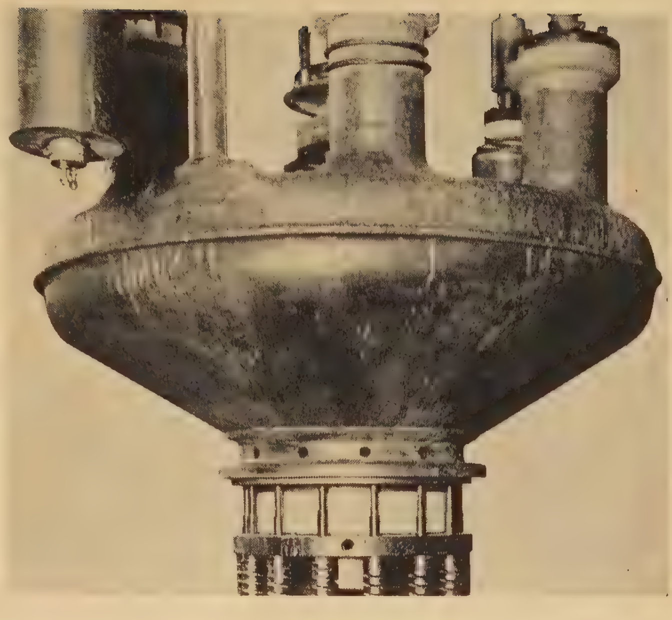


Figure 7. General Electric mercury-arc-rectifier vacuum chamber after eleven months' operation with sodium dichromate coolant in place of tap water showing corrosion arrested

Water has been found to be the most practical coolant where the heat to be removed is relatively high. In apparatus where the watts per square inch are relatively low, forced air, or circulating oil may be utilized. For certain applications, such as the cooling of rectifier mercury-condensation pumps, tap water cooling is the most practical. Here the amount of heat to be removed is small, the rate of water flow is low and the apparatus to be cooled is relatively small. The apparatus being small, makes it possible to confine the water cooling system in a copper jacket or copper cooling coils.

Low Ambient or Freezing Protection

Water cooling systems utilizing the recirculating principle can be protected from freezing by maintaining a higher temperature by means of jacket water heaters or by the use of a nonfreezing solution. Both systems have been found practical. Where tap water cooling is used, it may be necessary to lag the water piping sufficiently to prevent freezing, and insure that a constant water flow is maintained.

Maintenance of Cooling Systems

All cooling systems require a certain degree of maintenance, depending upon the nature or chemical content of the water used.

Closed cooling systems utilizing sodium dichromate as corrosion inhibitor have been found to require the least attention. Many systems have operated for several years without the necessity of cleaning.

Tap water-cooled apparatus must be descaled frequently to prevent water stoppage. Here again the frequency of cleaning will depend upon the amount of mineral water in solution and the amount of matter in suspension, both of which will eventually clog the water system. Copper water piping is no exception. It also readily scales, but naturally will not corrode as iron pipe does. Water containing excessive amounts of chlorine has increased corrosion effect on iron piping. Water containing much algii, or manganese dioxide, makes frequent cleaning of the water system necessary.

Electrical Insulation of Water Systems

In order to insulate a water-cooled apparatus or a part of the apparatus from parts of higher or lower potential, the coolant is conducted through insulating tubing such as rubber hose or rigid tubing. The two ends of an insulating tubing containing a coolant in general form the terminals of an electrolytic cell. It is natural that electrolytic disintegration will be expected at the positive terminal with electrolytic deposition on the negative end. In order to retard the accelerating form of corrosion in the cooling system, so-called "electrolytic leads" have been applied which consist of a long metallic rod of positive potential which gradually disintegrates whenever a difference of potential exists in between the ends of the insulating tubing. The disintegration of the metallic rod prevents the metal ends of the insulating tubing from disintegrating and will last several months or years, depending upon the prevailing

A New Method for Introducing Relaxed Initial Conditions in Transient Problems

WALTER C. JOHNSON
ASSOCIATE AIEE

IN the calculation of transients in linear electrical and mechanical systems by the classical methods of differential equations, the constants of integration which arise in the solution are ordinarily evaluated from the initial values of the dependent variable and its derivatives.[1,2] The process of finding the initial derivatives is sometimes difficult for even rather simple systems, and the difficulties are particularly pronounced when the system of equations has undergone a change of variable to remove variable coefficients, as for example in Park's equations for the synchronous machine.[3] The purpose of this paper is to present a new method by which the initial derivatives can be found for an initially relaxed system (all currents in inductances and all charges on condensers initially zero) by a manipulation of the final differential equation itself. The solution for a nonrelaxed system can be found from the relaxed solution by superposition or by means of a systematic change in the original differential equations themselves, as is commonly done in operational calculus.[1,4,5]

The Differential and Integral Operators

The procedure in determining initial derivatives directly from the differential equation is based on the properties of the differential operator p (sometimes designated instead by the symbol D) and the integral operator $1/p$. It is shown in elementary treatments of linear constant-coefficient differential equations that if the derivative dy/dt be written py, where p indicates the operation d/dt, then p has many of the manipulative properties of an algebraic coefficient. Thus the second derivative d^2y/dt^2 can be represented by $p(py)$ or p^2y, and the integral with respect to time $\int y\,dt$, being the operation which cancels the first derivative, can be written symbolically $(1/p)y$. Similarly the iterated integral $\int\int..\int_n y dt$ is written $(1/p^n)y$.

In an initially relaxed system, all currents and voltages are zero for negative time. It is therefore possible in such a system to interpret the indefinite integral operator $1/p$ to mean the definite integral from 0– to t. The assignment of these limits does not interfere with the previous definition of $1/p$ as the indefinite integral, for the variable upper limit t provides this indefinite integral, and the lower limit merely supplies the proper constant of integration.

Examine next the integral $\int_{0-}^{t} y\,dt = (1/p)y$ as the upper limit of integration t approaches zero. It is evident from elementary integral calculus that under this condition the value of the integral approaches zero also, provided that y is not infinite at $t=0$. Thus we can write the useful relation

$$\lim_{t\to 0}\frac{1}{p}y=0 \tag{1}$$

which holds whenever the system is without energy at $t=0$, provided that y is finite at this time.

It will be observed that it is the quantity $(1/p)y$ and not $(1/p)$ itself which is zero at zero time. This is because $1/p$ is an operator and not merely a multiplier. The distinction will save much confusion, since if we wrote $1/p=0$ we should feel obliged to write $p=\infty$ at $t=0$. This, of course, is not correct, and will be avoided by observing that $(p)y$ is not the reciprocal of $(1/p)y$, and hence is not necessarily infinite when $(1/p)y$ is equal to zero.

The Problem

In the usual circuit problem a differential equation is set up for each mesh of the network, using Kirchhoff's laws. By expressing all of the derivatives and integrals in operator form and by manipulating the operator p as an algebraic coefficient, algebraic methods of solving simultaneous equations can be used to eliminate all of the dependent variables (e.g., currents) except the desired one. In doing this care must be exercised not to take any indicated derivatives but instead to retain all p's in operator form. By convention all operators are written to the left of the currents and voltages on which they operate. The resulting differential equation in terms of the desired variable is of the general form:

$$\phi(p)i=F_1(p)e_1(t)+F_2(p)e_2(t)+\ldots \tag{2}$$

in which

$e_1(t)$ is the voltage (in general a function of time) impressed in mesh number 1

$e_2(t)$ is the voltage impressed in mesh number 2, etc.

$\phi(p)$, $F_1(p)$, $F_2(p)$, etc., are polynomials in p

The polynomial $\phi(p)$ is generally as high or higher in degree of p than $F_1(p)$, $F_2(p)$, etc. If $\phi(p)$ is lower in degree of p than some $F(p)$, as is the case when solving for the current in a circuit in which a complete path through condensers exists between input terminals, the response i may contain an infinite impulse at $t=0$, and equation 1 will no longer hold. This difficulty can be eliminated by rewriting the differential equation in terms of charge q, where $pq=i$, and later taking the derivative of the solution for q to find the form of i.[1]

It is known from differential-equation theory that for any given system of differential equations there is one and only one set of solutions which is zero for negative time, and hence for any dependent variable in the system there is one and only one set of initial derivatives

Paper 41-38, recommended by the AIEE committee on basic sciences and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted September 11, 1939; made available for preprinting December 10, 1940.

WALTER C. JOHNSON is instructor in electrical engineering at Princeton University, Princeton, N. J.

1. For all numbered references, see list at end of paper.

difference of potential and the nature of the coolant.

References

1. MERCURY-VAPOR PRESSURE CONTROL OF MERCURY-ARC RECTIFIERS, E. J. Remscheid. *General Electric Review*, December 1938.

2. RETARDING CORROSION IN THE WATER SYSTEMS OF POWER RECTIFIERS, Charles Van Brunt and Emil J. Remscheid.

3. THE PASSIVITY OF METALS, PART VII; THE SPECIFIC FUNCTION OF CHROMATES, T. P. Hoar and U. R. Evans. *Journal of the Chemical Society*, part II, 1932, pages 2456–81.

4. METALLIC CORROSION PASSIVITY AND PROTECTION, U. R. Evans, page 324.

which satisfy the condition of initial relaxation. We now desire to obtain directly from the differential equation 2 the values of these derivatives of the dependent variable i as t approaches zero from the positive side. In general, if $\phi(p)$ is of the nth degree, it is sufficient to know the initial values of the dependent variable and its first $n-1$ derivatives.

The Procedure

Since we know from the discussion in a preceding section that for an initially relaxed nonimpulsive system all integrals of current and voltage must be zero at $t=0$, it is advantageous to first put the differential equation 2 into integral form by dividing through by p to the highest power found in $\phi(p)$.* It will then be found that by making t and the various integrals $1/p$, $1/p^2$, etc., equal to zero everywhere in the integral equation, the initial value of current, $i(0)$, can be found immediately. Here t is considered to approach zero from the positive side.

To find the initial value of the first derivative of current, $i'(0)$, take the first derivative of the integral equation in a symbolic manner by multiplying through by p, take all indicated derivatives (denoting them by primes where necessary), and again set t and the various integrals $1/p$, $1/p^2$, etc., equal to zero everywhere. Solve for i', which will be di/dt at $t=0$ or $i'(0)$, where t is considered to approach zero from the positive side.

To obtain the initial value of the second derivative, multiply the integral equation through by p^2 and repeat the process. This procedure can be continued indefinitely until the required number of initial derivatives has been found. The process must be a successive one since each derivative will be expressed in terms of lower derivatives.

Since the method requires only the formation of the integral equation and the application of the fact that in an initially relaxed nonimpulsive system the various integrals of current and voltage are zero at $t=0$, it is simpler to apply the process to each problem separately without attempting to derive formulas.

Examples

(1) An A-C Circuit

The differential equations for the circuit shown in figure 1 can be written as:

$$(R+1/pC)i_1-(1/pC)i_2=E\sin\omega t$$
$$(-1/pC)i_1+(1/pC+pL)i_2=0 \qquad (3)$$

*For a proof of the method, see the appendix.

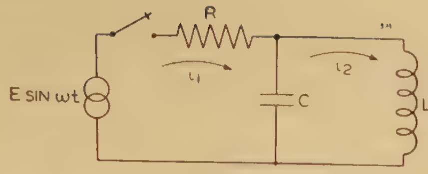


Figure 1. Circuit of example number 1

The elimination of i_2 by algebraic methods yields:

$$\left(RLp^2+\frac{L}{C}p+\frac{R}{C}\right)i_1=\left(Lp^2+\frac{1}{C}\right)E\sin\omega t \qquad (4)$$

The steady-state current can be found by the usual complex 'mpedance method:

$$i_{ss}=\frac{E}{|Z|}\sin(\omega t-\phi)$$

where

$$Z=R+j\frac{\omega L}{1-\omega^2LC}$$

and

$$\phi=\tan^{-1}\frac{\omega L}{R(l-\omega^2LC)}$$

If the roots of the characteristic equation $(m^2RL+mL/C+R/C)=0$ are $m=-a_1$, $-a_2$, the total current is given by the expression:

$$i_1=\frac{E}{|Z|}\sin(\omega t-\phi)+C_1\epsilon^{-a_1t}+C_2\epsilon^{-a_2t} \qquad (5)$$

where C_1 and C_2 are the constants of integration to be determined from the initial conditions.

To find the relaxed initial derivatives, return to differential equation 4 and rewrite it as an integral equation by dividing through by p to the highest power found on the left side, p^2. This yields:

$$\left(RL+\frac{L}{C}\frac{1}{p}+\frac{R}{C}\frac{1}{p^2}\right)i=\left(L+\frac{1}{C}\frac{1}{p^2}\right)E\sin\omega t \qquad (6)$$

For the initial value of ', set t and the integrals $1/p$ and $1/p^2$ equal to zero in the integral equation 6. Then we have

$$(RL+0+0)i=(L+0)E\sin(0)$$

or

$$i(0)=0$$

For the initial value of di/dt, take the first derivative of the integral equation 6 by multiplying through by p. Then, taking the indicated derivatives and setting t and the various integrals equal to zero, we obtain:

$$RLi'(0)+\frac{L}{C}i(0)+0=LE\omega\cos(0)+0$$

or, since $i(0)=0$,

$$i'(0)=\frac{\omega E}{R}$$

Substituting these two conditions for time $t=0$ into the solution 5 and its first derivative, two equations in terms of the Cs are obtained:

$$C_1+C_2=\frac{E}{|Z|}\sin\phi$$

$$a_1C_1+a_2C_2=\omega E\left[\frac{\cos\phi}{|Z|}-\frac{1}{R}\right]$$

When the equations are solved simultaneously for the Cs, and these substituted into equation 5, the result is the complete solution for an initially relaxed system:

$$i_1=\frac{E}{|Z|}\left[\sin(\omega t-\phi)+\frac{(R\omega\cos\phi-Ra_2\sin\phi-\omega|Z|)\epsilon^{-a_1t}+(Ra_1\sin\phi-R\omega\cos\phi+\omega|Z|)\epsilon^{-a_2t}}{R(a_1-a_2)}\right]$$

(2) Solution of an Oscillatory Circuit

The circuit shown in figure 2 is one in which the initial value of the first derivative of input current is very difficult to find by ordinary means, and where the operational solution becomes rather laborious because of complex quantities which must be rationalized.

The differential equation for the input current can be shown to be:

$$\left[p^2L(R_1+R_2)+p\left(R_1R_2+\frac{L}{C}\right)+\frac{R_1}{C}\right]i=\left(p^2L+pR_2+\frac{1}{C}\right)E \qquad (7)$$

If the circuit is oscillatory a convenient form of the solution is:

$$i=\frac{E}{R_1}+\epsilon^{-at}(A\sin\omega t+B\cos\omega t) \qquad (8)$$

where

$$a=\frac{R_1R_2+L/C}{2L(R_1+R_2)}$$

$$\omega=\sqrt{\frac{R_1}{LC(R_1+R_2)}-\frac{(R_1R_2+L/C)^2}{4L^2(R_1+R_2)^2}}$$

To find the successive initial derivatives, first obtain the integral equation by dividing differential equation 7 through by p^2. Set the various integrals equal to zero and obtain

$$[L(R_1+R_2)+0+0]i=(L+0+0)E$$

or

$$i(0)=\frac{E}{R_1+R_2}$$

To find the initial value of the first derivative, multiply the integral equation through by p, take the indicated derivatives, and set the various integrals

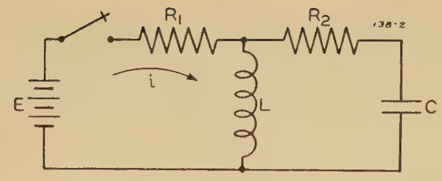


Figure 2. Circuit of example number 2

equal to zero. This yields

$$L(R_1+R_2)i'(0)+(R_1R_2+L/C)i(0)+0=0+R_2E+0$$

and since the value of $i(0)$ has just been found, we can solve for the desired $i'(0)$, obtaining:

$$i'(0)=\frac{E(R_2^2-L/C)}{L(R_1+R_2)^2}$$

If these values of i and i' are substituted into the solution 8 and its first derivative at $t=0$, we find that

$$A=\frac{E}{2\omega L(R_1+R_2)^2}\left[R_2^2-\frac{L}{CR_1}(2R_1+R_2)\right]$$

$$B=\frac{-ER_2}{R_1(R_1+R_2)}$$

The complete solution for relaxed initial conditions can now be written from equation 8 by substitution of these values for A and B. The solution has been obtained in a simple and direct manner, and has avoided a rather laborious manipulation of complex numbers.

Appendix—Proof of Method of Determining Initial Derivatives

Consider the system of differential equations:

$$\sum_{=1}^{n}(a_{ij}p+b_{ij})x_j=f_i(t),\quad i=1,2..n \tag{9}$$

Let this system be written in terms of continuous variables, for example if current is discontinuous, write the equations in terms of charge. Where second derivatives occur, introduce a new variable z such that:

$$px_j-z_j=0 \tag{10}$$

The second derivative p^2x_j can then be written pz_j, and equation 10 will form part of system 9.

Since the system is linear, the various terms $f(t)$ can be introduced one at a time, and the total solution found by the superposition of the separate solutions. It is therefore sufficient to prove that the method is correct with only one $f(t)$ present. Hence let:

$$\begin{aligned} f_i(t)&=f(t) &&\text{for } i=1\\ &=0 &&\text{for } i\neq 1 \end{aligned} \tag{11}$$

First find the initial values of the derivatives of x_k by solving the system of equations 9 for time $t=0$. To do this, transpose the b-terms of equations 9, thus obtaining:

$$\sum_{j=1}^{n}a_{ij}x_j'=f_i(t)-\sum_{j=1}^{n}b_{ij}x_j \tag{12}$$

where x_j' represents px_j or dx_j/dt.

The independent variables are continuous, so $x_j(0+)=0$. Let $t=0$ in equations 12 and solve the system for $x_k'(0+)$. Then:

$$x_k'(0+)=\frac{M_{1k}}{D}f(0+) \tag{13}$$

where D is the determinant of the a's, and M_{1k} is the minor obtained by striking out the first row and kth column of this determinant and attaching the sign $(-1)^{k+1}$.

Differentiate equations 12 once, set $t=0$, substitute equation 13, and solve for $x_k''(0+)$, which is d^2x_k/dt^2 at $t=0+$.

$$x_k''(0+)=\frac{M_{1k}}{D}f'(0+)-\frac{f(0+)}{D^2}\sum_{i=1}^{n}\sum_{j=1}^{n}b_{ij}M_{ik}M_{1j} \tag{14}$$

This process can be continued indefinitely to find the initial values of higher derivatives.

It will now be shown that the same results are obtained by means of the new method. Return to the original system of equations 9 and eliminate all of the dependent variables except x_k. This yields:

$$(A_0p^n+A_1p^{n-1}+..+A_n)x_k=(B_1p^{n-1}+B_2p^{n-2}+..+B_n)f(t) \tag{15}$$

where

$$A_0=D$$

$$A_1=\sum_{i=1}^{n}\sum_{j=1}^{n}b_{ij}M_{ij} \tag{16}$$

$$\vdots$$

$$B_1=M_{1k}$$

$$B_2=\sum_{i=2}^{n}\sum_{\substack{j=1\\ j\neq k}}^{n}b_{ij}M_{1i,jk}$$

$$\vdots$$

in which $M_{1i,jk}$ represents the second minor of the determinant D obtained by striking out the first and ith rows and the jth and kth columns, and attaching the sign $(-1)^{1+i+j+k}$ for $j>k$ and $(-1)^{i+j+k}$ for $j<k$.

Applying the new method of determining initial values of derivatives to equation 15, we find that:

$$x_k(0+)=0 \tag{17}$$

$$x_k'(0+)=\frac{M_{1k}}{D}f(0+) \tag{18}$$

$$x_k''(0+)=\frac{M_{1k}}{D}f'(0+)+\frac{f(0+)}{D^2}\left[\sum_{i=2}^{n}\sum_{\substack{j=1\\ j\neq k}}^{n}b_{ij}DM_{1i,jk}-\sum_{i=1}^{n}\sum_{j=1}^{n}b_{ij}M_{ij}M_{1k}\right] \tag{19}$$

Equation 17 is correct by virtue of the continuity of the x's, equation 18 checks with equation 13 as obtained by the other method, and comparison of equation 14 with equation 19 shows that the following condition must be satisfied:

$$\sum_{i=1}^{n}\sum_{j=1}^{n}b_{ij}M_{ik}M_{1j}=\sum_{i=1}^{n}\sum_{j=1}^{n}b_{ij}M_{ij}M_{1k}-\sum_{i=2}^{n}\sum_{\substack{j=1\\ j\neq k}}^{n}b_{ij}DM_{1i,jk} \tag{20}$$

The coefficients of the b's must be separately equal. Because of the conditions on the last summation, three cases must be distinguished:

Case I. $i=1$, j unrestricted

The coefficients of b_{1j} as obtained from equation 20 are:

$$M_{1k}M_{1j}=M_{1j}M_{1k}$$

which is an identity.

Case II. i unrestricted, $j=k$

The coefficients of b_{ik} in equation 20 are:

$$M_{ik}M_{1k}=M_{ik}M_{1k}$$

Case III. $i\neq 1$, $j\neq k$

The coefficients of b_{ij} yield the following relation which must be satisfied:

$$M_{ik}M_{1k}-M_{ik}M_{1j}=D\cdot M_{1i,jk} \tag{21}$$

The left side of equation 21 can be written as an nth order determinant, which, when multiplied by the determinant D rearranged with the former kth and jth columns as the first and second columns, and with the former ith row shifted to the second row, yields the following result:

$$\begin{vmatrix} a_{1k} & a_{1j} & a_{11} & \ldots & a_{1n}\\ a_{ik} & a_{ij} & a_{i1} & \ldots & a_{in}\\ a_{2k} & 2_{2j} & a_{21} & \ldots & a_{2n}\\ \vdots & \vdots & \vdots & & \vdots\\ . & . & . & & .\\ a_{nk} & a_{nj} & a_{n1} & \ldots & a_{nn} \end{vmatrix}\cdot\begin{vmatrix} M_{1k} & M_{ik} & 0 & 0 & \ldots & 0\\ M_{1j} & M_{ij} & 0 & 0 & \ldots & 0\\ M_{11} & M_{i1} & 1 & 0 & \ldots & 0\\ M_{12} & M_{i2} & 0 & 1 & \ldots & 0\\ \vdots & \vdots & \vdots & \vdots & & \vdots\\ M_{1n} & M_{in} & 0 & 0 & \ldots & 1 \end{vmatrix}=$$

$$\begin{vmatrix} D & 0 & a_{11} & \ldots\ldots & a_{1n}\\ 0 & D & a_{i1} & \ldots\ldots & a_{in}\\ 0 & 0 & a_{21} & \ldots\ldots & a_{2n}\\ \vdots & \vdots & \vdots & & \vdots\\ \vdots & \vdots & \vdots & & \vdots\\ 0 & 0 & a_{n1} & \ldots\ldots & a_{nn} \end{vmatrix}$$

The left side is equal to $(-1)^{i+j+k+1}D[M_{ij}M_{1k}-M_{ik}M_{1j}]$ for $j>k$ and to $(-1)^{i+j+k}D[M_{ij}M_{1k}-M_{ik}M_{1j}]$ for $j<k$. The right side, when expanded, is found to be equal to $(-1)^{i+j+k+1}D^2\cdot M_{1i,jk}$ for $j>k$ and to $(-1)^{i+j+k}D^2\cdot M_{1i,jk}$ for $j<k$, so therefore:

$$M_{ij}M_{1k}-M_{ik}M_{1j}=D\cdot M_{1i,jk}$$

which was to be proved.

If the differential equation 15 had been written in terms of a variable with a simple discontinuity at $t=0$, say in terms of the first derivative of x_k, each term on the right side of equation 15 would have been raised once in power of p. The method will yield

The Varioplex—a New Development in Telegraphy

E. R. SHUTE
MEMBER AIEE

Synopsis: The varioplex method of telegraphic operation provides each pair of stations connected together by it an ever-ready two-way channel for the exchange of traffic, which occupies a band width of zero when idle and of a variable width when busy, depending upon extent of simultaneous usage by other connected stations. It possesses certain advantages over, or in supplement to, other forms of manual and machine switching or repeatering. Adapted to the use of private subscribers through telemeter service, it is finding extensive application in the telegraph plant.

A GOOD deal of current effort in the telegraph engineering field is being directed toward the solution of problems of trunking and switching. Basically, these problems arise from the circumstance that important trunking centers, like Boston, Atlanta, or Los Angeles, have tributary to them most of the less important telegraph offices in their respective surrounding areas. That this is so with respect to the many branch telegraph offices and tie-line connections which dot the larger American cities requires no explanation; the growth of commerce along the railroads has made it no less true of cities and towns many miles from trunking centers. The existence of fanned-out local telegraph circuits around Boston as a hub, to take that city as an example, is inherent in the commercial relationship of most New England towns to its dominating city. It can be appreciated, then, why the Boston office, in years past, has acted not only as the terminal for a considerable day-to-day traffic between Taunton and Boston but also as the relay point for the less frequent messages between Taunton and New York. This situation exists the country over. Of recent years, improvements in the transmission qualities of these tributary circuits have made it possible to terminate them, almost universally, in printing telegraph equipment.

Between the larger cities for years there have existed the more heavily loaded trunk wires, over which has flowed traffic manually fed to them by the tributary networks. Through the use of synchronously-operating multiplex distributors, the capacity of these intercity trunk facilities has been made conveniently divisible into units called traffic channels, of an output adapted to the capabilities of operators. These channels operate at speeds of from 60 to 75 words per minute. The gradual standardization of printer equipment, the stabilization of unit capacities, and the adaptability of printer circuits to end-on repeatering have together extended an open invitation to engineers to increase the number of trunk channels regularly connected, or temporarily connected on demand, to other trunk channels and to fanned-out tributary trunks and tie lines, thus markedly increasing the number of pairs of cities, pairs of towns, of branch offices, and of customers, directly tied together by traffic channels.

In creating such through channels between distant terminals, recourse has been had to end-on switching of a variety of types of circuit constituting the intervening geographical circuit sections. Some have been of start-stop, others of the multiplex time-division, or sector, type; some have been routed over duplexed ground-return physical conductors, others over metallic loops, or over composite or superimposed d-c pairs, or over a-c carriers; and either with or without electromechanical storage en route.

The type of switching adopted for increasing the length and number of these standard-width traffic channels has been influenced in part by the holding time of the connections. Where day-by-day connection of intercity trunks has been desirable, fork-series connection of multiplex channels,[1] and extended start-stop channels,[2] have produced efficient results. Where telegraph-talk connections have had to be quickly set up and pulled down[3] in a manner similar to that employed in connecting long-distance telephone calls, the general pattern of toll switching[4] has been followed. Where the bulk of the traffic is single-shot, forms of dial machine switching[5] have proved advantageous. In the admixture of all types of traffic in a large office installation, the manual switching of reperforators[6] has been successful. All these methods have been, and still are, significant in telegraphy as it is being developed in the United States today.

The Varioplex Concept

Whatever the form of switching, switched telegraph channels, up until the present time, have had in common the characteristic of occupying a frequency band of constant width, whether busy or idle. Although not standardized, such bands have been of the order of 20 cycles per second in width, accommodating traffic at a rate, representatively, of 65 words a minute.

Against the foregoing background of progress, Philo Holcomb, Jr., the author of a companion paper[7] before this convention, originally projected the concept of, and devised the circuits for, a telegraphic "lane" for traffic, of variable, rather than of constant, width—a lane whose width occupied the full capacity of a geographical circuit section at times when that lane alone was being accommodated—a lane whose width adjusted itself automatically to occupy only its proportionate share of a component circuit section at times when that circuit section was simultaneously accommodating other lanes of traffic—and, most important of all, a lane for traffic whose

Paper 41-22, recommended by the AIEE committee on communication and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 8, 1940; made available for preprinting December 3, 1940.

E. R. Shute is vice-president of the Western Union Telegraph Company, New York, N. Y.

1. For all numbered references, see list at end of paper.

---

the proper initial values in this case also, for the initial value of the new variable will be equal to the first derivative of the old, and so on. The method is therefore applicable to variables with a simple discontinuity at $t=0$, as well as to variables which are continuous everywhere.

References

1. Operational Circuit Analysis (a book), **Vannevar Bush.** John Wiley and Sons, pages 48–55 and 291–334.

2. Communication Networks (a book), **E. A. Guillemin.** McGraw-Hill Book Company, volume I, chapter VI.

3. Two-Reaction Theory of Synchronous Machines, Part I, Generalized Method of Analysis, **R. H. Park.** AIEE Transactions, volume 48, July 1929, pages 716–30.

4. Operational Methods in Mathematical Physics (a book), **H. Jeffreys.** Cambridge Tract in Mathematics and Mathematical Physics No. 23, 1927, Cambridge University Press, chapter 1.

5. A Simple Proof and Extension of Heaviside Operational Calculus, **Balth. Van der Pol.** *Philosophical Magazine*, vii, 1929, page 1153.

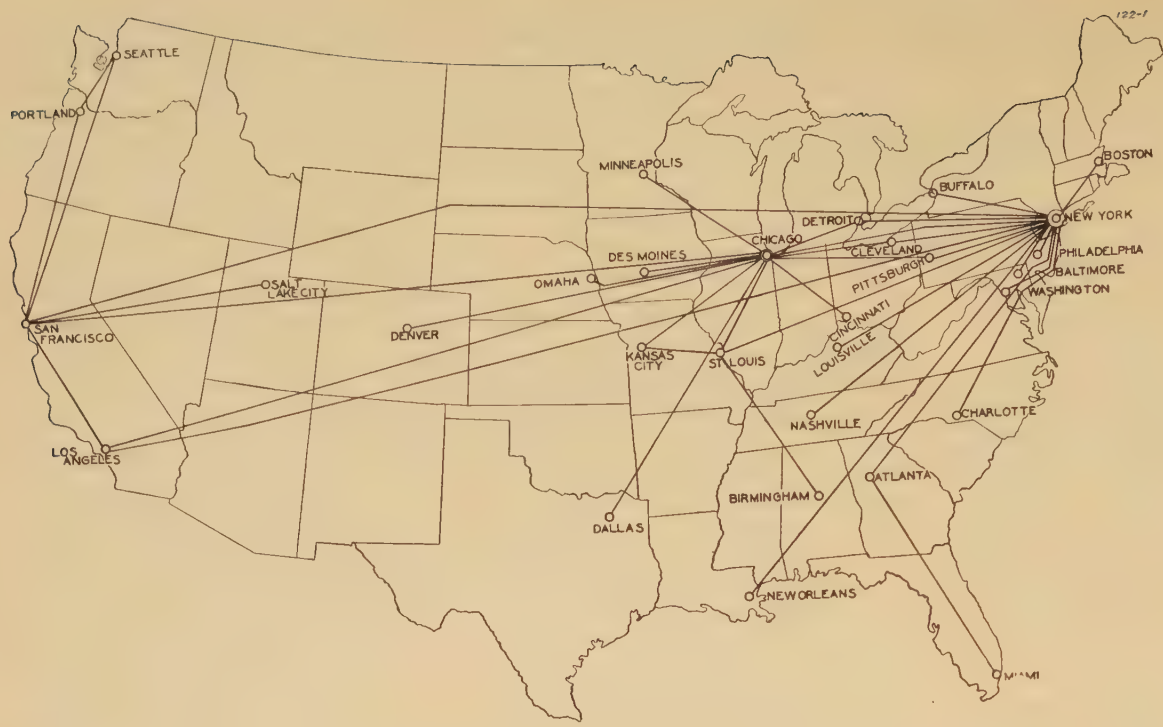


Figure 1. Map of varioplex systems in United States

width decreased to zero, automatically, whenever no traffic happened to be passing over the lane.

It was at once obvious that with such an expanding, contracting, variable-width lane, it would be practicable, ultimately, to set up a multiplicity of direct connections theretofore considered out of the question because of light loads. For the lane width now having been reduced to zero when idle, there remained no necessity to deny to two telegraph offices or to two tie-line customers or subscribers a direct lane for traffic merely because the load offered happened to be small in relation to the total capacity of a 20-cycle-per-second channel of multiplex over which it might be switched.

An important part of the concept was that the effect of switching thus secured was to be accomplished, not manually as by a plug-and-jack switchboard, nor automatically as by dialing a number, but by the expedient of providing that the two terminals should always remain interconnected through the system but completely "inert" until traffic was offered. The fundamental switched informational unit was to be, not the duration of a toll call, not the length of a series of messages or even of one telegram, but the amount of information transmitted by the operator without pause, be that the extreme length of a press dispatch or, at the other extreme, the length of one word, a numeral, or even a solitary letter.

Applications

The original concepts and circuits were developed by the Western Union engineering department and the systems given the name of varioplex. The map, figure 1, shows the extent of application of such systems, and the photograph, figure 2, depicts the installation of 4 out of the 16 systems terminating in the main telegraph office in New York City. The 39 systems operate over 92 channels of standard duplex multiplexing equipment and provide 736 unidirectional lanes, or 368 two-directional "subchannels" as they are referred to, of communication.

A typical varioplex system is that set up between Los Angeles and San Francisco, consisting of 27 subchannels. Twenty-two of the 27 subchannels provide direct two-way printer operation between 22 pairs of San Francisco and Los Angeles branch offices or subscribers' tie lines, the business between which hitherto would have had to be carried on 22 individual wires or manually relayed in San Francisco and again in Los Angeles. The remaining five subchannels provide Los Angeles Western Union with direct connection to offices in Seattle, Chicago, Sacramento, Oakland, and Reno, through flexible linkage at San Francisco. In the case of the Seattle connection, the Los Angeles-San Francisco varioplex subchannel is connected to a San Francisco-Seattle varioplex subchannel; a similar connection is made at San Francisco on a varioplex subchannel going through to Chicago. In the case of Sacramento and Oakland, physical wires carrying start-stop teleprinter signals between those cities and San Francisco are repeatered separately at San Francisco into the two varioplex subchannels to Los Angeles. In the case of Reno, a multiplex channel

Figure 2. Four of 16 systems of varioplex apparatus in New York main office

between Reno and San Francisco is coupled to the Los Angeles varioplex subchannel at San Francisco.

Capacity

Sixty-six words per minute has been adopted as the standard multiplex channel speed for varioplex systems. The total capacities of such systems are, therefore, 66, 132, 198, and 264 words per minute in each direction, depending upon whether the varioplex system is carried over one, two, three, or four channels of multiplex. The Los Angeles-San Francisco system referred to is of 264 words capacity.

Some idea of the flexibility of varioplex systems may be gained by consideration of the equipment of three multiplex channels on a physical wire (or two unidirectional channels of audio-frequency telegraph carrier) between New York and St. Louis. One of the channels is retained in use as a duplex printer trunk; the second carries a three-subchannel varioplex system; the third carries a six-subchannel varioplex. By way of comparison, the Chicago-Los Angeles varioplex of six subchannels occupies the combined capacity of all three multiplex channels.

The type of varioplex system chosen and the number, type, and traffic loading of the subchannels assigned to it, are matters tied up with the time, frequency, and duration of the occurrence of peaks of simultaneous demand for facilities. The maximum number of subchannels now assigned to a varioplex system in service is 36. It is thought that this figure by no means represents the upper limit of lightly loaded subchannels which ultimately will economically be so assigned. If all 36, or all 48, 99, or whatever the upper limit may prove to be—if all the connected load were to demand simultaneous use of the circuit, the speed per channel would be very low indeed, the total to be divided among all being only, say, 264 words per minute. In practice, however, the maximum simultaneous demand has been recorded at only nine subchannels on this 36 subchannel system; each channel was operating at 29 words per minute during the period of maximum demand. The usual condition of simultaneous demand has been found to lie between two and five channels on this 36 subchannel system. Since all subchannels enjoy full speed of 66 words per minute on this circuit until the fifth subchannel cuts in, it may be said that only occasionally is the speed ever reduced from that figure, and in such cases only down to 53 words per minute for brief intervals.

When, because too large a number of varioplex subchannels are in simultaneous use their respective speeds are unreasonably low, the obvious cure is to reassign the subchannels. Examination into the causes of abnormal simultaneous usage has often pointed the way to corrective action. Low subchannel speed is not a defect of the varioplexing process, for the situation on the superseded multiplex under the conditions of manual operation and with the same concentrated fall of traffic would be even worse. For a given fall of traffic the varioplex packs the informational content more compactly into the available transmission band width than does any other form of telegraphy. If a multiplex circuit between New York and Seattle has a capacity of 100 messages per hour and satisfactorily handles all the traffic on a manual-relay basis between the New York and Seattle areas, experience has pointed to the conclusion that all the offices in those areas could, if desired, be interconnected by varioplex over the long haul and there would be no excessive demand peak, and no unreasonably low channel speeds would be encountered. In fact, it would be found that more offices and more traffic could be added to the connected load without encountering trouble.

Occasional reduction of speed is noticeable to a receiving operator watching a printer working on a varioplex subchannel. From the viewpoint of the sending operator, however, there is no difference between varioplex and teleprinter transmission. The line from the sending printer on each operating table is connected to an individual distributor and automatic perforator combination at the varioplex terminal, shown in figure 3. This combination converts the seven unit start-stop signals from the sending printer keyboard to a perforated paper tape in the usual five-unit multiplex code. The sending line and distributor-perforator combination are continuously available to the operating table so that the sending operator may send at any time at the full teleprinter speed of 65 words per minute. Thus is met the requirement of a continuously available full-speed channel for the transmission of traffic from the operating position. Regardless of the speed variations that may exist in transmitting the characters over the trunk channels, the full capacity and efficiency of the sending operator may be utilized whenever traffic is on hand for transmission.

Advantages

Regardless of the extent to which the varioplex has already been installed, its full potentialities in increasing the efficiency of utilization of trunk circuits and equipment may not yet have been fully realized. A telegraph informational transmission band is essentially very narrow—of the order of 20 cycles per second or less, as pointed out before. To assign a physical wire to its transmission is an unconscionable waste from an engineer's standpoint. To assign to it a carrier with comparatively wide intercarrier spacing is only slightly more pardonable. Interlocking multiplexed channels are more efficient as to band width occupied, but even here the fixed width of each of the channels admits of no conformation either to the human limitations of the operators or to the vagaries of the fall of traffic. Surveys of trunk groups with a mixture of physical, derived, and carrier circuits employed in diverse services have shown an unused capacity as high as 70 per cent on facilities considered "full." Divided into units of capacity of 60 to 70 words per minute, there were, literally, no facilities to be spared in the groups under survey. Only by varioplexing all facilities in such circuit groups can 100 per cent utilization be approached. One great contribution of the varioplex to the telegraph art is that its flexibility makes available for traffic many of the heretofore idle cracks and corners of the telegraph wire-plant capacity.

A second important advantage of the varioplex is that no matter how heavily congested one or more of the circuit sections may be over which the lane for traffic is connected, transmission of the first character of every message initiated is started immediately and completed forthwith, from origin to destination, as soon as the keyboard is manipulated. There is no testing for idle channels, no busy signals are received, no time is wasted in handling dial-switching impulses, there is no additive delay due to such impulses traversing the chain of connection, no waiting for a particularly long message to clear out of the way. Since all varioplex connections are, in essence, perpetually connected two-way circuits, there is no waiting involved on the part of the sending office for a quick acknowledgment of receipt on the part of the receiving office.

A third major advantage which the varioplex contributes to the art is the compounding of possibilities of elimination of manual relaying of telegraphic information. While other modern meth-

Figure 3. Racks containing equipment for nine type C varioplex subchannels

ods of switching channels accomplish a similar purpose, their scope has been limited by the requirement that, to justify economical switching, the switched informational unit must contain a practical minimum number of words. Elimination of such an economic minimum through the varioplex principle throws open a wide field of development for switching, with all its demonstrated advantages over manual relaying. The number of operations and the amount of supervision are reduced—so are investment, operating maintenance, and inspection costs of belt conveyors, branch-office pneumatic tubes, printers, perforators, typewriters, and stationery. So too are routing and servicing costs cut down. Because varioplex repeaters require much less room than corresponding channels for manual relaying, there are additional savings in rental items.

A fourth advantage of the varioplex is, in a sense, a derivative of the other three in their application to the use of public telegraph facilities by private communication systems. By employing varioplex subchannels, users need no longer choose between the continuous utilization of a full standard-width communication channel on the one hand and a discontinuous service on the other. Varioplex connections between two private customers afford them teleprinter intercommunication at any time without the necessity of ordering a circuit to be made up and without any impulse to hurry or terminate a conversation through lapse of time alone. Opportunity is thus afforded for deliberation between questions and answers and for consulting files, assistants, and authorities. To utilize a varioplex subchannel for this type of service it is necessary only to present a sufficient volume of traffic to pay the costs of providing the subchannel equipment; the charge may then be based on volume rates for the traffic actually handled. A metering instrument incorporating a character counter has been developed for such an application, and the varioplex facility is now widely used by subscribers under the name of telemeter service.

Conclusion

The increase in the efficiency of utilization of trunk-circuit capacity effected by the use of varioplex equipment is an obvious and worth-while contribution to telegraph progress. The dissociation of subchannels for point-to-point communication from the use of trunk-circuit capacity except when traffic is actually being transmitted is reflected in a greater return on investment in lines and terminal equipment. In laying out point-to-point channels for the handling of commercial telegraph traffic operating engineers need no longer be bound by former limitations as to traffic volumes. To establish a direct channel of communication, a volume of traffic sufficient to justify the use of a fixed amount of trunk-circuit capacity represented by at least one full trunk channel has in the past been necessary. Assuming that the total traffic between the areas concerned justifies the use of varioplex equipment as many individual subchannels as needed can be set up, it being necessary for the loads on these individual subchannels to be sufficient to justify only the subchannel operating equipment and the equipment for connecting it into the varioplex system. This possibility is further multiplied through the interconnection of subchannels from two or more systems to effect direct connections between areas not directly served by individual varioplex systems.

Experience is now beginning to reveal the optimum economic usage of methods of machine-switching, reperforation, and varioplex. Many interesting combinations are possible. Long-haul, intercity varioplex channels may be dialed by various branch offices in the city of origin, and fanned out by manually-switched reperforators in the cities of destination. Thus is indicated a material increase in the number of direct connections between telegraph offices and a resulting better telegraph service to the American public.

References

1. Telegraph Traffic Engineering, **H. Mason** and **C. J. Walbran.** AIEE Transactions, volume 46, February 1927, page 379.

2. Annual Report of the Committee on Communication. AIEE Transactions, volume 50, 1931, pages 1488–94.

3. The 1-A Teletypewriter Switchboard, **A. A. Burgess.** *Bell Laboratories Record*, volume 16, October 1937, pages 34–8.

4. A General Switching Plan for Telephone Toll Service, **H. S. Osborne.** AIEE Transactions, volume 49, October 1930, pages 1549–57.

5. Some Recent Developments in Teleprinter Switching Systems, **P. J. Clemens.** *Electrical Communication*, volume 16, January 1938, pages 263–75.

6. Recent Developments in Telegraph Switching, **F. E. d'Humy** and **H. L. Browne.** AIEE Transactions, volume 59, February 1940, pages 71–8.

7. Basic Principles of the Varioplex Telegraph, **Philo Holcomb, Jr.** AIEE Transactions, volume 60, 1941.

Transactions Section

Preprint of Corresponding Pages From the Current Annual Transactions Volume

Any discussion of these papers will appear in the June 1941 "Supplement to Electrical Engineering—Transactions Section"

Power Supply for Resistance-Welding Machines—III

Factory Wiring for Resistance Welders

AIEE COMMITTEE ON ELECTRIC WELDING

Subcommittee on Power Supply for Welding Operations*

Purpose of Report

AN adequate power supply is one of the requisites of present-day, high-production resistance welding. A major part of the power supply system of any industrial plant lies within the plant itself and consists of the plant wiring and transformer substations. It is the purpose of this report to show how to properly lay out such a plant distribution system for serving welders. Much of the fundamental data included in the tables and charts is not new but is included in order that the layout engineer will have complete information available in one compact report and will not have to refer to various articles and handbooks, copies of which may not be readily available.

General Considerations

The first report of this series, "Guide to Good Electrical Performance of Resistance Welding Machines," pointed out the need for keeping welder kilovolt-ampere inputs as low as possible for given welding current outputs, and the next step consists of providing adequate supply facilities for handling these inputs. Because of the high currents involved, transformers should be located as close to the welders as possible, keeping the secondary bus and feeder runs short. In many cases it will be found advantageous to use transformers containing a liquid that will not burn rather than oil in order that they can be located adjacent to the welding machines rather than at some relatively remote outdoor or vault location. With the load power factor generally falling between 20 and 40 per cent, it is essential that the reactance of the power supply system be kept at a minimum. Generous copper cross section in welding feeders is usually less important than proper spacing and arrangement of the conductors for minimum reactance.

The first question to be answered is: "For what voltage drop shall the supply system be designed?" No specific answer can be given which will apply to all cases and, as pointed out in the preceding report, satisfactory results may be obtained with 15 per cent regulation in one case and 5 per cent may be too much in another. However, in general with the usual class of production resistance welding involving low and medium carbon steels, satisfactory welding will result if the voltage drop to a point on the supply system common to two or more machines does not exceed ten per cent for the largest machine of the group. This statement is based on the assumption that there are relatively few large machines in the group being served (say, not over five or ten machines) and that, while two of them may occasionally operate at the same time, the chances of three or more operating together is extremely remote. Thus, if the machines are adjusted for perfect welding with a ten per cent voltage drop in their supply circuit, the welds will still be good when two machines operate together causing nearly 20 per cent drop. If three or more happen to hit together, poor welds or rejects may result. Care should be exercised in adjusting machines, with the setting made under highest voltage and maximum current conditions, just short of burning the weld so that under minimum voltage conditions a good weld will still result.

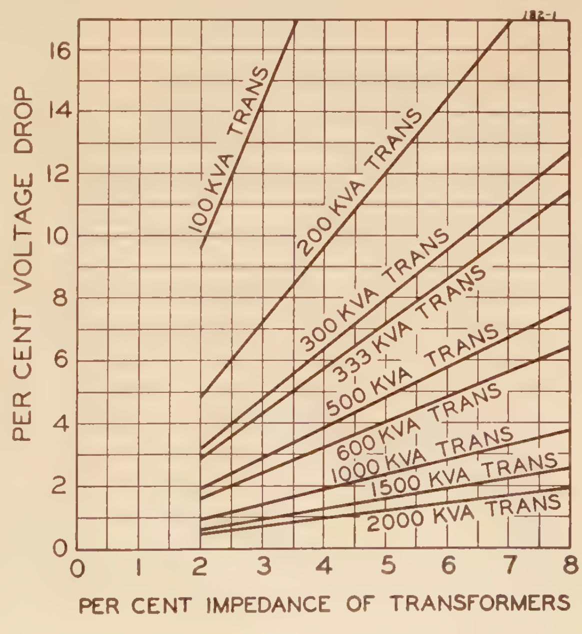


Figure 1. Welding supply—transformer regulation

Per cent voltage drop per 1,000 amperes of 30 per cent power factor, single-phase welding current

1. For 480-volt, single-phase transformer bank, use chart values of per cent voltage drop
2. For 480-volt, three-phase transformer bank, multiply per cent voltage drop by 2
3. For 240-volt, single-phase transformer bank, multiply per cent voltage drop by 1/2
4. For 240-volt, three-phase transformer bank, use chart values of per cent voltage drop

---

Paper 41-82, recommended by the AIEE committee on electric welding, and presented at the AIEE North Eastern District meeting, Rochester, N. Y., April, 30–May 2, 1941. Manuscript submitted November 12, 1940; made available for preprinting March 1, 1941.

*Personnel of AIEE subcommittee on power supply for welding operations: L. W. Clark, *chairman;* E. F. Dissmeyer, M. B. Gathman, C. E. Heitman, W. F. Hess, E. A. Hester, H. S. Hubbard, S. M. Humphrey, A. H. Lewis, G. S. Mikhalapov, C. L. Pfeiffer, F. H. Roby, and F. E. Sanford.

1. For all numbered references, see list at end of paper.

Experience indicates that this general rule of ten per cent drop for the largest machine will result in a good workable installation in most cases although it should be realized there will be exceptions. The procedure outlined in the following sections will follow the ten-per-cent rule with some indication as to how to determine those installations which will require special consideration as exceptions to the general rule.

Where even less than ten per cent regulation can be provided at about equal cost, such as obtained by close spacing of feeders, this obviously should be done. The ten-per-cent figure is set only as an approximate allowable upper limit and any improvement below this value is all to the good and makes for that much better welding conditions.

Interlocking can be resorted to under some conditions to insure not more than one or two machines operating at the same time. This is an inexpensive practice where only a few large machines are involved and in most cases production speed is not materially reduced.

While the current-carrying capacity of the supply feeders and transformers must receive consideration, if provision is made to keep the voltage drop within the necessary limits, there usually will be sufficient attendant thermal or carrying capacity.

Voltage Drop

For convenience, the supply system can be broken up into three parts:

1. High-voltage power supply system (2,400 volts or higher)
2. Step-down transformer bank
3. Low-voltage bus or feeder (240 or 480 volts)

High-Voltage Power Supply System

The high-voltage power supply system in most cases is the power company's service to the plant. Where the plant generates its own power, it is typified by the generator bus system. In most cases very little can be done toward reducing the voltage drop in the high-voltage power supply system at a cost commensurate with the expenditure needed for the same percentage reduction in the low-voltage system.

In the case of service from a power company, the amount of voltage drop for a given welding load is dependent upon the relative location of the industrial plant with respect to the power company's large distribution substations as well as generating stations. If the plant is in an established industrial area served by large substations and not too far from large generating stations, the voltage drop in the high-voltage system will be a negligible factor. However, if the plant has been located in a rural or small-town area far removed from the power company's main generating stations, as is becoming more common under the present-day trend toward decentralization of industry in the search for low manufacturing costs and reduced taxes, the high-voltage system regulation may loom up as a very troublesome factor. Any plant in which resistance welding is extensively used should carefully investigate this matter of high-voltage system regulation when contemplating moving the plant to any other location with less adequate power facilities for welding.

In the case of private power generation, the voltage drop at the generator bus will be inversely proportional to the total rating of generators feeding the bus. The small and moderately sized plant will experience considerable difficulty in handling any but the smaller-sized welding machines without encountering lamp flicker problems in their plant and office lighting.

The first step in designing the plant wiring and bus layout for welding is to determine the high-voltage system regulation. This can be obtained from the local power company by giving them the maximum kilovolt-amperes and power factor that the largest machine will draw from the power system. Subtract the figure obtained from the total allowable ten per cent and the remainder is that which can be allowed in the step-down bank and secondary or low-voltage bus system. For instance, assume the largest welder is rated 300 kva and will deliver a maximum welding current of 100,000 amperes with a high secondary open circuit voltage of 8 volts. The approximate maximum kilovolt-ampere input (neglecting exciting current) is $(100,000\times8)/1,000=800$ kva. From the power company representative it is learned that 800 kva at an estimated 30 per cent power factor will cause four per cent drop in the power company service to the transformer bank at the customer. This subtracted from ten per cent leaves six per cent which can be used up in the step-down transformers and low-voltage bus system.

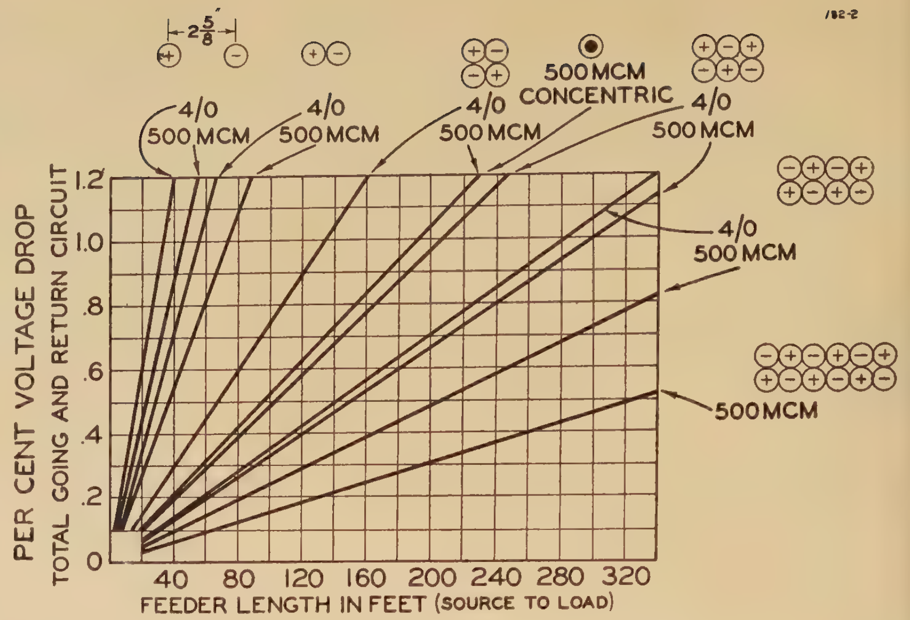


Figure 2. Welding supply—wire feeder regulation

Per cent voltage drop per 1,000 amperes of 30 per cent power factor, single-phase welding current

1. For 480-volt feeder, use chart values of per cent voltage drop
2. For 240-volt feeder, multiply per cent voltage drop by 2

Step-Down Transformer Bank

On the assumption that the remaining allowable six per cent drop can be divided about equally between the step-down transformer bank and low-voltage bus system, it is necessary to select the proper size transformer which will limit the drop to about three per cent.

Welders can either be served from a single-phase transformer bank or a three-phase bank, and where the welding load is large enough to justify a separate transformer bank for welding load only, it will be found advantageous and more economical of capacity to use a single-phase system. The load is single phase and it will remain single phase no matter

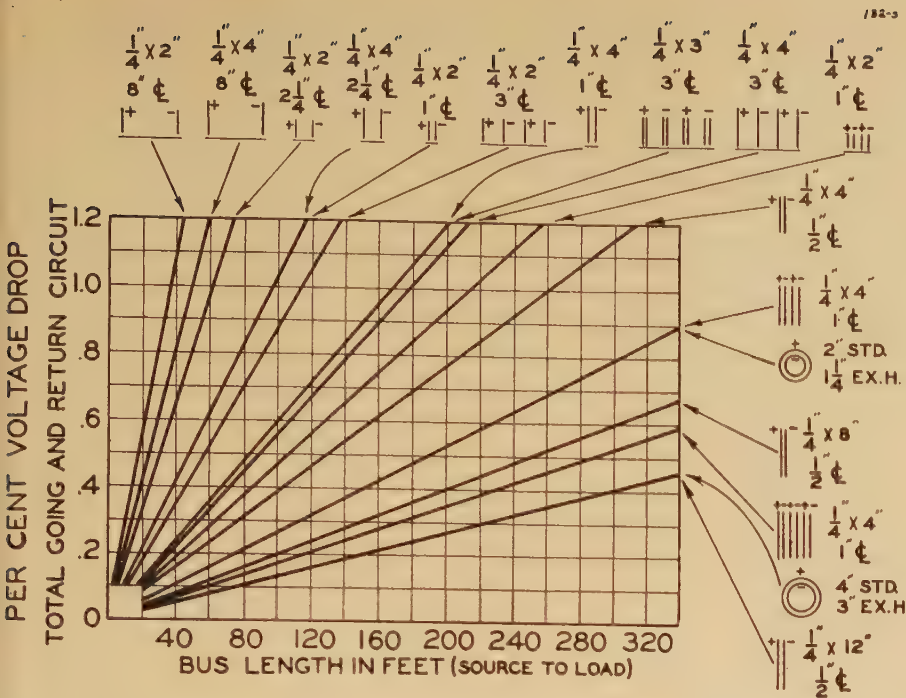


Figure 3. Welding supply—bus regulation

Per cent voltage drop per 1,000 amperes of 30 per cent power factor, single-phase welding current

1. For 480-volt bus, use chart values of per cent voltage drop
2. For 240-volt bus, multiply per cent voltage drop by 2

how the transformers ahead of it are connected. Sometimes it is desirable to spread the individual single-phase loads over the three-phase wires for more economical utilization of the supply lines, but unless there are large numbers of machines connected, the necessity for balancing the load is not important. When there are many machines, they are usually scattered around in different parts of the plant so that several step-down banks become necessary at different locations. In this case individual single-phase banks can be connected to separate phases and thus bring about some semblance of balance on the supply wires.

A given kva of single-phase load fed from a three-phase transformer bank will cause just twice as much transformer voltage drop as the same kva load fed from the same capacity in transformers connected as a single-phase bank. It is thus obvious that, where the transformer voltage drop must be kept at a minimum, it is highly desirable and more economical to use single-phase, step-down banks of transformers.

In case the welding load is relatively small in comparison with the motor and other power load of the plant, it can readily be served from the same three-phase bank serving the power load. Individual plant and service conditions thus dictate whether single-phase or three-phase banks are the logical selection. Irrespective of whether the welding load is served from single-phase transformers or from three-phase transformers in combination with the motor and power load, the lighting load should usually be handled separately in order to prevent flicker difficulties.

Figure 1 shows per cent voltage drop per 1,000 amperes of 30 per cent power factor welding current through transformer banks of different sizes and impedance. Plant practice may determine the size and impedance of individual transformers and the number of units to connect in parallel can be determined from the chart. For instance, assume that 300-kva, $3^1/_2$-per-cent-impedance transformers are used by this particular plant in its step-down banks. A load of 800 kva represents 1,670 amperes at 480 volts. From figure 1: 1,670 amperes through a 300-kva, $3^1/_2$-per-cent-impedance transformer causes 1.67 times 5.6 per cent = 9.4 per cent = voltage drop. Therefore, three transformers in parallel would have to be used to stay within the predetermined limit of three per cent drop. In some cases a special low-impedance transformer may be economically justified. For example, if a two-per-cent-impedance transformer is purchased, the nearest size transformer would be 500 kva which would allow 3.2 per cent drop. This might be cheaper than the three 300-kva transformers but would have the definite disadvantage of not being usable interchangeably at other plant locations. If a plant has sufficient welding load, it sometimes pays to standardize on special low-impedance transformers for welding only and not attempt to make them interchangeable with transformers used in power and lighting banks.

Low-Voltage Bus or Feeder

There is now only three per cent remaining out of the original allotted ten per cent drop. It is found that the bus or feeder must be 300 feet in length to reach the two machines located farthest from the transformer bank.

Figures 2 and 3 show the per cent voltage drop per 1,000 amperes of 30 per cent power factor welding current for different types and sizes of bus and wire construction. Figure 2 is for various wire arrangements and figure 3 for different bus arrangements. Some plant engineers prefer one class of construction and some the other. The bus can be made up on the job or it can be purchased, prefabricated in unit lengths either with or without enclosures.

Usually if the welders are in a fairly compact group but at some appreciable distance from the transformer bank, some arrangement of wire feeder works out to advantage. However, where the machines are scattered and frequent taps must be made to the supply wires or bus, a bus system is perhaps more advantageous in that frequent connections to it are readily made.

From the charts it is found that two 500,000-circ-mil wires per leg in conduit would handle 800 kva with 2.6 per cent drop at the 300-foot distance. (800 kva = 1,670 amperes. From the chart the drop for 150 feet = 0.78 per cent; for 300 feet and 1,670 amperes the voltage drop equals 0.78 per cent times 2 times 1.67 = 2.6 per cent.) For the bus construction a bus consisting of two $^1/_4$-inch by 4-inch copper bars on one-inch

Table I. Equivalent Continuous Loading of Typical Welding Machine Installations

Types of Welding	Equivalent Continuous Load Expressed in Per Cent of Sum of Name-Plate Ratings
Spot, projection, flash	5 to 10 (most installations); 10 to 20 (very few installations)
Hydromatic, butt	10 to 20
Seam	25 to 70

centers would be suitable from a voltage-drop standpoint.

It is possible that either of these selections may have sufficient current-carrying capacity for handling the equivalent steady or thermal load of the group of welders. However, if it is found that more carrying capacity is needed, other configurations are shown with equal or better voltage-drop characteristics.

Equivalent Continuous Thermal Loading

There are several ways in which the equivalent continuous thermal loading of a group of welders can be determined. It might be reasoned that the quickest and simplest method would be to add the name-plate kilovolt-ampere ratings of the individual welding transformers, and then apply a suitable diversity factor for group operation. The welding transformers are rated on a 50-per-cent duty-cycle basis and, consequently, if all of the machines are operated continuously right up to the thermal capacity of their transformers, the equivalent continuous thermal loading would be $\sqrt{0.50}$ or 70.7 per cent of the sum of the name-plate ratings. Thus, if there were ten 300-kva welders, the supply system on this basis should have a carrying capacity of 70.7 per cent of 3,000 kva, or 2,100 kva less the diversity factor correction.

In actual practice, however, most machines, except perhaps some seam welders, operate well below their maximum thermal capacity, because the size of transformer in the machine is dictated by the required welding current output rather than by thermal considerations.

Tests of many installations show that the values given in table I are more clearly representative of actual field conditions. Thus, if the machines are predominately spot, projection, or flash welders, a supply system with a rating of 15 per cent of the sum of the name-plate ratings of the machines would, in most cases, be adequate. Thus, taking the ten 300-kva welders, the supply system should be good for about 15 per cent of 3,000 kva, or 450 kva.

A second check should be made based upon the actual kilovolt-ampere loads of the welders and their operating duty cycles. Assume that each of the ten 300-kva machines was on a production schedule of 100 welds per hour with maximum loads of 800 kva for 10 cycles per weld. The corresponding duty cycle of each machine is: $(10\times100)/(60\times60\times60)=0.46$ per cent. The equivalent continuous load corresponding with 800 kva at 0.46 per cent duty cycle is: $\sqrt{0.0046\times800}$ kva $=54$ kva. For the total of ten machines, if all were operating at peak production, the equivalent kilovolt-amperes would be $10\times54=540$ kva.

The selection of three 300-kva transformers on the basis of voltage-drop considerations is thus perfectly safe from the standpoint of current-carrying capacity. The 500-kva, 2-per-cent-impedance transformer might be just a little small from a thermal capacity standpoint for ten machines in peak production but, with the usual diversity of group operation, should be adequate.

Tables II and III show the equivalent carrying capacity in continuous amperes of the various types of bus and wire arrangements commonly used. The ampere load corresponding with an equivalent continuous thermal load of 500 kva at 480 volts is approximately 1,000 amperes. Thus, the wire construction previously selected on the basis of voltage drop is not large enough from the standpoint of current-carrying capacity. A wire grouping consisting of four 500,000-circ-mil wires per leg (item 11, table II) is rated about 1,000 amperes and should be adequate for the job. This wire arrangement will have only 1.2 per cent voltage drop for an 800-kva load swing, thus being well within the three per cent allowed.

It should be emphasized here that the current-carrying capacities given in table II for six or more total wires in a trough or raceway enclosure are estimated values only and while considered to be reasonable approximations, they are subject to change whenever verifying test data become available. The current-carrying capacities for most of the bus arrangements in table III are extrapolated from test data of similar configurations both in the open and in metal enclosures and should, consequently, be reasonably accurate although here again, actual test data would be welcomed by the industry.

Similarly, table III shows several types of bus construction well within the three-per-cent voltage-drop allowance which will have adequate carrying capacity. The original selection of one 1/4-inch by 4-inch bar per leg on one-inch centers would be adequate if mounted in the open. However, most bus installations will require enclosures and on this basis the selection would be between the heavier current-carrying busses having drops of less than three per cent.

Chance of Simultaneous Welds

Designing for a total of ten per cent voltage drop for the operation of the largest machine produces satisfactory welding conditions only when three or more machines do not happen to operate at the same instant. Based upon the general law of averages, the expectancy of simultaneous welds can be readily calculated. For the sake of simplicity, it is assumed that even if only a single

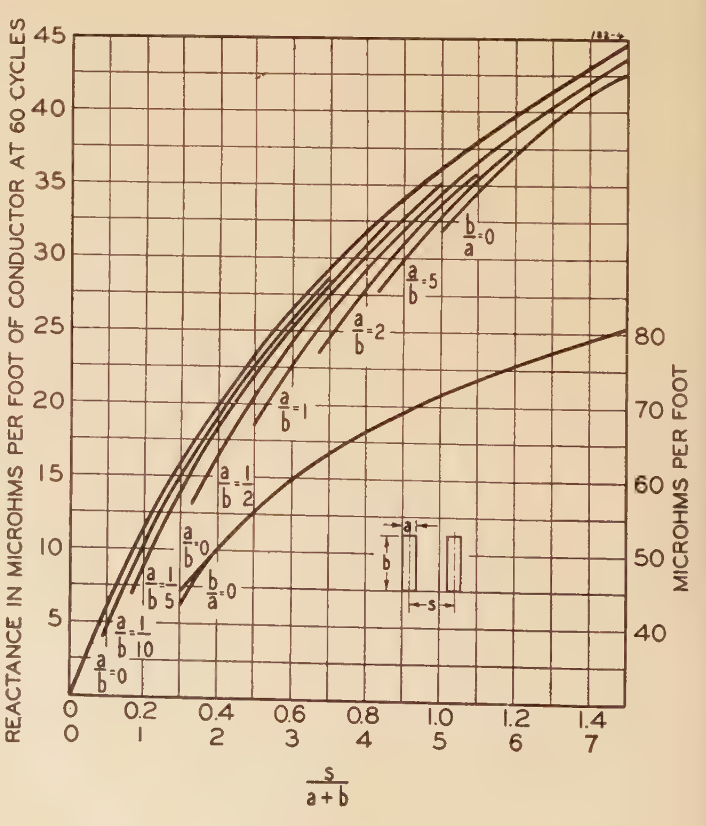


Figure 4. Reactance of strap conductors at 60 cycles

Table II. Welding Supply—Wire Feeder Data. Calculated Data Per 100 Feet of Distance From Source to Load (200 Feet of Circuit)

Item	Wires Per Leg	Spacing (See Figure 2)	Size	Area Square Inches	Approximate Current-Carrying Capacity Copper 60 Deg C Ambient 30 Deg C (Amperes)	Weight (Pounds)	D-C Resistance 25 Deg C (Ohms)	Reactance (Ohms)	Voltage Drop Per 1,000 Amperes 30 Per Cent Power Factor: Volts	Voltage Drop Per 1,000 Amperes 30 Per Cent Power Factor: Per Cent at 480 Volts
1	1	2 5/8-inch centers	4/0	0.166	225[1]	131	0.01	0.012	14.3	2.98
2	1	2 5/8-inch centers	500,000 circ-mil	0.393	400[1]	308	0.0043	0.0098	10.7	2.22
3	1	Wires laced together	4/0	0.166	210[2]	131	0.01	0.0059	8.72	1.82
4	1	Ditto	500,000 circ-mil	0.393	350[2]	308	0.0043	0.0056	6.63	1.38
5	2	Ditto	4/0	0.332	400[2]	261	0.0051	0.0022	3.63	0.76
6	1	Concentric cable	500,000 circ-mil	0.393	300[5]	308	0.0043	0.0013	2.53	0.53
7	2	Wires laced together	500,000 circ-mil	0.786	650[2]	616	0.0022	0.002	2.54	0.53
8	3	Ditto	4/0	0.498	500[3]	392	0.0034	0.0014	2.36	0.49
9	4	Ditto	4/0	0.664	600[3]	522	0.0026	0.001	1.72	0.36
10	3	Ditto	500,000 circ-mil	1.18	850[3]	925	0.0014	0.0013	1.63	0.34
11	4	Ditto	500,000 circ-mil	1.58	1,000[3]	1,230	0.0011	0.00089	1.17	0.24
12	6	Ditto	500,000 circ mil	2.36	1,300[3]	1,850	0.00072	0.0006	0.79	0.17

Notes: 1. Code limit.
2. In conduit, wires laced together.
3. In trough, wires laced together (estimated values—no test data known).
4. Reactance is slightly higher when wire is in magnetic trough or conduit.
5. In conduit (estimated value—no test data known).

cycle of one weld overlaps another, this would constitute a simultaneous weld. Obviously, except for very short-time welds (two to three cycles), a single cycle overlap should not prove serious and this assumption thus introduces a considerable factor of safety.

T = total time per weld per machine, including "off" and loading time as well as actual weld time

t = actual weld time per machine

E = number of machines

$\frac{T}{tE}\times\frac{T}{t(E-1)}$ = interval in terms of number of welds between operations in which *two* machines make a weld at the same time including any slight overlapping of actual welding time

$\frac{T}{tE}\times\frac{T}{t(E-1)}\times\frac{T}{t(E-2)}$ = interval in terms of number of welds between operations in which *three* machines make a weld at the same time including any slight overlapping of welding time

In usual production welding if rejects due to simultaneous welds do not occur oftener than once per hour, which would be one weld out of every 5,000 or 10,000, conditions would probably be considered highly satisfactory. Table IV shows various combinations of machines, welding time, hourly production, and corresponding interval of time between expected simultaneous welds. For instance, 20 machines with three-cycle welding can produce 200 welds per hour per machine with an expectancy of three simultaneous welds and three rejects every 1.7 hours. With the production stepped up to 300 welds per hour per machine, the resultant expected interference might be such that it would be desirable to either split the machines into two groups or design for a five per cent instead of ten per cent voltage drop in the supply system.

The last column shows total time divided by the actual weld time of all large machines on the bus. As long as this value is greater than 10 or 20, satisfactory welding conditions should generally result on a supply system with ten per cent voltage drop, as the chances of three simultaneous welds occurring oftener than once per hour is rather remote. (For exceptions see last paragraph.) It should be remembered that these considerations apply only to the large machines. Innumerable small machines can be served from the same transformer bank and bus system along with the five or ten large machines, upon which the distribution system design is based, without any further consideration except that of thermal carrying capacity of the system.

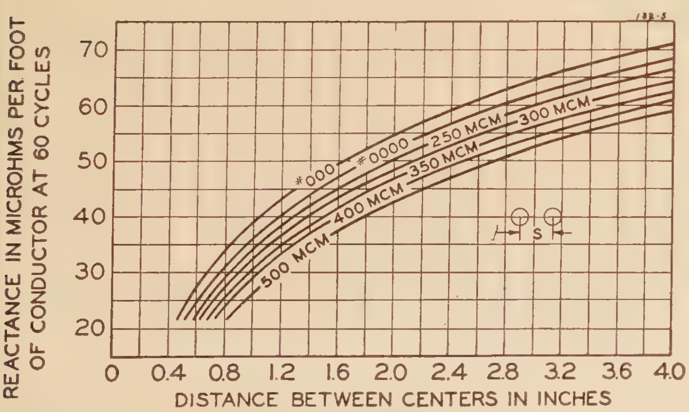


Figure 5. Reactance of standard strand cables at 60 cycles

It might not be amiss in this connection to point out another frequently encountered cause of poor welding in addition to that of excessive voltage regulation. There is a tendency on the part of many users of welding equipment to increase the welding speeds far beyond the capacity of the equipment to make good welds. As a result, a certain percentage of such welds are inferior. The designer then specifies a greater number of welds in an attempt to assure himself of a sufficient number of good welds to produce a satisfactory joint. The production department must then make these welds at an even faster rate of speed to maintain costs, resulting in an even greater number of inferior welds.

This vicious circle of events can be eliminated by insistence upon good welding throughout, resulting in fewer welds per joint, which in turn permits welding speeds commensurate with good welding. This results in better voltage regulation by reducing the chances of simultaneous or interfering welds on any given feeder line.

There may be some classes of welding where every weld must be perfect and there must be no chance of even a few undetected poor welds passing inspection. In these cases it may be desirable to design for closer regulation. However, even under these conditions, the extra investment needed for reduced regulation should be balanced against the cost of necessary recorders and indicators for detecting welds made under improper conditions of voltage, current, and time

It might be more economical to invest in the recorders and indicators than in excessive feeder and transformer capacity which would only be needed once or twice a day when three or more machines might happen to hit together.

Example. Ten 300-kva machines, each machine producing 100 welds per hour of 10 cycles duration each:

$$T=\frac{60\times 60\times 60}{100}=2{,}160 \text{ cycles}$$

$t=10$ cycles

$E=10$ machines

$\frac{T}{tE}\times\frac{T}{t(E-1)}=\frac{2{,}160}{10\times 10}\times\frac{2{,}160}{10\times 9}=518$ welds between operations in which *two* machines make a weld at the same time

Total output $=1{,}000$ per hour

Two welds together every $(518\times 60)/1{,}000 = 31$ minutes

$\frac{T}{tE}\times\frac{T}{t(E-1)}\times\frac{T}{t(E-2)}=\frac{2{,}160}{10\times 10}\times\frac{2{,}160}{10\times 9}\times\frac{2{,}160}{10\times 8}=14{,}000$ welds beween operations in which *three* machines make a weld at the same time

Three welds together every $14{,}000/1{,}000 = 14$ hours

Total time divided by weld time of all welders $=(60\times 60\times 60)/(10\times 10\times 100) = 21.6$

Interlaced Bus Calculations

The reactance values of the various wire groupings and bus-bar configurations shown in figures 2 and 3 and in tables II and III were calculated by means of the following short-cut method, utilizing the charts of reactance for a pair of conductors (either for conductors, figure 4, or standard strand cables, figure 5).[1] In this way it is possible to calculate the reactance of an interlaced bus or cable system with a reasonable degree of accuracy in a few minutes, as compared with the more laborious method based upon the fundamental relations of mutual and self-inductance which at best requires several hours.

This short-cut method of calculation is incorporated as part of this report in order that quick calculations can be made for other wire or bus configurations than those shown in the tables.

The basic methods and curves used here are not new, but were published in U. S. Bureau of Standards Scientific Paper No. 281 by Francis B. Silsbee, and also in *The Electric Journal* of June 1919 in an article entitled "Reactance Values for Rectangular Conductors" by H. B. Dwight. However, it was felt desirable to bring together all of the necessary data for the calculation of welder bus reactance and to show by actual examples the use of these data for the calculation of interlaced conductors.

The more general types of welder busses which are commonly used are: (1) four or more stranded insulated conductors interlaced and clamped together, (2) interlaced copper bars, and (3) concentric tubes. Figures 4 and 5 show the total reactance, self minus mutual, between two conductors. The same curves can be used in the following manner when more than two conductors are involved and there is an even number of conductors. Consider an interlaced bus consisting of six conductors, three going and three returning, as shown in item 15, table III, arranged as follows:

(+1) (−4) (+2) (−5) (+3) (−6)

Since the average drop of the going circuit equals the average drop of the return circuit, it is only necessary to find the drop in the going circuit and multiply it by two to determine the total circuit drop. If, as a first approximation, it is assumed that the current divides evenly between all of the going conductors, the reactance of any going conductor is the sum of the reactances of all the return conductors to the given going conductor minus the reactance of the remaining two going conductors to the given going conductor. Dividing the sum of the reactances of the going conductors by three gives the average going reactance per conductor and dividing this average by three (since it is assumed that only one-third of the current went through each conductor) gives the going circuit reactance. Multiplying this value by two gives the total circuit (going plus return) reactance.

The reactance of each going conductor can be written as follows:

$$X_1=X_{14}+X_{15}+X_{16}-X_{12}-X_{13}$$
$$X_2=X_{24}+X_{25}+X_{26}-X_{21}-X_{23}$$
$$X_3=X_{34}+X_{35}+X_{36}-X_{31}-X_{32}$$

The total circuit reactance (going plus return) is:

$$X_T=\frac{2}{9}(X_1+X_2+X_3)$$

It should be pointed out that, although this method is approximate, it is ac-

Table III. Welding Supply—Bus-Bar and Tubing Data. Calculated Data Per 100 Feet of Distance From Source to Load (200 Feet of Circuit

Item	Bars Per Leg	Spacing (See Figure 3)	Size (Inches)	Area Square Inches	Approximate Current-Carrying Capacity 35-Deg C Rise (Amperes)		Weight (Pounds)	D-C Resistance 25 Deg C (Ohms)	Reactance (Ohms)[3]	Voltage Drop Per 1,000 Amperes 30 Per Cent Power Factor	
					Open	Housing[2]				Volts	Per Cent at 480 Volts
1	1	8″ centers	1/4x2	0.5	750	490	386	0.0033	0.0126	13.0	2.71
2	1	8″ centers	1/4x4	1.0	1,400	950	772	0.0017	0.0098	9.84	2.05
3	1	2 1/4″ centers	1/4x2	0.5	750	490	386	0.0033	0.0072	7.86	1.64
4	1	2 1/4″ centers	1/4x4	1.0	1,400	950	772	0.0017	0.0048	5.07	1.06
5	1	1″ centers	1/4x2	0.5	720	450	386	0.0033	0.0041	4.91	1.02
6	2	3″ centers interlaced	1/4x2	1.0	1,400	950	772	0.0017	0.0039	4.19	0.87
7	1	1″ centers	1/4x4	1.0	1,370	900	772	0.0017	0.0025	2.88	0.60
8	2x2	3″ centers interlaced	1/4x3	3.0	3,600	2,600[4]	2,315	0.00056	0.0028	2.84	0.59
9	2	3″ centers interlaced	1/4x4	2.0	2,600	1,800[4]	1,544	0.00084	0.0026	2.73	0.57
10	2	1″ centers interlaced	1/4x2	1.0	1,350	870	772	0.0017	0.0018	2.25	0.47
11	1	1/2″ centers	1/4x4	1.0	1,370	900	772	0.0017	0.0014	1.83	0.38
12	2	1″ centers interlaced	1/4x4	2.0	2,500	1,700[4]	1,544	0.00084	0.0011	1.27	0.26
13	1	2″ Standard tube around 1 1/4 extra heavy tube		1.09 0.89	800		765	0.0017	0.00078	1.25	0.26
14	1	1/2″ centers	1/4x8	2.0	2,600	1,800[4]	1,544	0.00084	0.00076	0.98	0.20
15	3	1″ centers interlaced	1/4x4	3.0	3,500	2,400[4]	2,315	0.00056	0.0007	0.83	0.17
16	1	4″ Standard tube around 3 extra heavy tube		3.18 3.05	2,000		2,410	0.00054	0.0005	0.64	0.13
17	1	1/2″ centers	1/4x12	3.0	3,600	2,500[4]	2,315	0.00056	0.0005	0.64	0.13

NOTES: 1. Extrapolated from test data.
2. Housing material, size, and color affect rating to marked degree.
3. Reactance may be as much as 5 per cent to 20 per cent higher if bus is in magnetic housing.
4. Nonmagnetic housing.

Table IV. Chance of Simultaneous or Interfering Welds

Number of Machines	Weld Time (Cycles)	Welds Per Hour Per Machine	Total Output Per Hour	Time Interval Between Simultaneous Welds: Two Welds Together	Time Interval Between Simultaneous Welds: Three Welds Together	Number of Good Welds for Every Weld in Which Three Hit Together	Total Time Divided by Weld Time of All Welders
5	3	100	500	52 hr	12,500 hr	6,250,000	144
5	3	200	1,000	6.5 hr	777 hr	777,000	72
5	3	300	1,500	1.9 hr	154 hr	231,000	48
5	10	100	500	4.2 hr	336 hr	168,000	43
5	10	200	1,000	35 min	21 hr	21,000	22
5	10	300	1,500	10 min	4.2 hr	6,200	14
3	30	100	300	2.9 hr	207 hr	62,200	24
3	30	200	600	22 min	13 hr	7,760	12
3	30	300	900	6 min	2.6 hr	2,310	8
5	30	100	500	31 min	12.4 hr	6,220	14
5	30	200	1,000	4 min	47 min*	778	7
10	3	100	1,000	5.8 hr	518 hr	518,000	72
10	3	200	2,000	43 min	32.4 hr	65,000	36
10	3	300	3,000	13 min	6.4 hr	19,200	24
10	10	100	1,000	31 min	14 hr	14,000	22
10	10	200	2,000	4 min	52 min*	1,743	11
10	10	300	3,000	1 min	10 min*	520	7
10	30	100	1,000	3 min	28 min*	467	7
20	3	100	2,000	41 min	27 hr	54,000	36
20	3	200	4,000	5 min	1.7 hr	6,840	18
20	3	300	6,000	2 min	20 min*	2,020	12
20	10	100	2,000	4 min	44 min*	1,480	11

*Note: On border line of unsatisfactory operating conditions if supply system is designed for ten per cent voltage drop for operation of largest machine. For these conditions supply system should probably be designed for about five per cent voltage drop.

curate within ten per cent which is good enough for most practical calculations.

Numerical Example 1. Determine the reactance of an interlaced bus 1,000 feet long, consisting of $^1/_4$-inch by 4-inch copper bars spaced one-inch center-to-center as shown in table III, item 15. The distance between the center lines of each conductor and all of the other conductors should be calculated and the reactances corresponding to these distances should be obtained from figure 4.

For example, the distance between the center lines of conductors 1 and 4 is $1'' \times \frac{S}{a+b} = \frac{1''}{^1/_4''+4''} = 0.235$ and the corresponding reactance is 0.0125 ohm per 1,000 feet. The remaining reactances can be found in a similar manner.

$$X_1 = 0.0125+0.0290+0.0392-0.0220-0.0347=0.0240$$

$$X_2 = 0.0125+0.0125+0.0290-0.0220-0.0220=0.0100$$

$$X_3 = 0.0290+0.0125+0.0125-0.0347-0.0125=-0.0027$$

$$X_T = \frac{2}{9}(X_1+X_2+X_3) = \frac{2}{9}(0.0249+0.0100-0.0027) = 0.00696 \text{ ohm (going and return)}$$

The same method can be used on stranded cables, except that the reactance values are taken from figure 5.

Numerical Example 2. Determine the reactance of six 250,000-circ-mil interlaced standard-strand, rubber-insulated cables 1,000 feet long and arranged similar to item 8, table II, arranged as follows:

(+1) (−4) (+2)
(−6) (+3) (−5)

The copper diameter is 0.576 inch, the rubber thickness is 0.094 inch, and the braid thickness is 0.020 inch, giving a total diameter of 0.804 inch. The distance between the center lines of each conductor and all of the other conductors should be calculated and the corresponding reactances should be obtained from figure 5.

The distance between the center lines of conductors 1 and 3 is $\sqrt{0.804''+0.804''} = 1.138$ inches and the corresponding reactance is 0.0368 ohm per 1,000 feet. The remaining reactances can be found in a similar manner.

$$X_1 = 0.0288+0.0288+0.0473-0.0448-0.0368=0.0233$$

$$X_2 = 0.0288+0.0473+0.0288-0.0448-0.0368=0.0233$$

$$X_3 = 0.0288+0.0288+0.0288-0.0368-0.0368=0.0128$$

$$X_T = \frac{2}{9}(X_1+X_2+X_3) = \frac{2}{9}(0.0233+0.0233+0.0128) = 0.0132 \text{ ohm (going and return)}$$

The reactance of concentric tubular busses is easily expressible in a formula. Let the outer radius of the outer tube be r_4, the inner radius of the outer tube be r_3, the outer radius of the inner tube be r_2, and the inner radius of the inner tube be r_1. The reactance then can be expressed as:

$$X = 11.49\left[4.606\left(\log_{10}\frac{r_3}{r_2} + \frac{r_1^4}{(r_2^2-r_1^2)^2}\log_{10}\frac{r_2}{r_1} + \frac{r_4^4}{(r_4^2-r_3^2)^2}\log_{10}\frac{r_4}{r_3}\right) - \frac{r_2^2+r_1^2}{2(r_2^2-r_1^2)} - \frac{r_4^2+r_3^2}{2(r_4^2-r_3^2)}\right]\times 10^{-3}$$

where X is in ohms per 1,000 feet of bus (total going and return circuit)

Feeder Data for Small Installations

In cases of small installations of welders served at low voltage (240 or 480 volts) by the power company the plant wiring will generally consist of wires pulled in conduit. It is usually unnecessary to lace the going and return wires together for minimum spacing before pulling in conduit, as the natural positioning of the wires in the conduit will give close enough spacing.

Table V gives the impedances of circuits and current-carrying capacities of relatively small wires suitable for small installations.

Table V.—Impedance and Carrying Capacity of Conductors in One Conduit

Wire Size	Conduit Size (Inches)	Resistance One Conductor Per 1,000 Feet (Ohm)	Reactance One Conductor Per 1,000 Feet (Ohm)	Current-Carrying Capacity (Amperes) Copper, 60 Deg C Ambient, 30 Deg C
2	$1^1/_4$	0.156	0.040	107
0	$1^1/_2$	0.098	0.041	139
2/0	2	0.078	0.038	160
3/0	2	0.062	0.036	182
4/0	2	0.049	0.038	210

Typical Examples

Example 1. Small Job-Welding Shop

Machines:
One 150-kva seam welder
Four 20-kva spot welders

Maximum kilovolt-ampere load swing of largest machine:
1,500 amperes at 240 volts = 360 kva

Regulation for 360 kva:

	Per Cent
1. Supply system (4,800 volts)	3.0
2. 200-kva, single-phase, 4,800/240-volt, 3-per-cent, Z transformer	5.5
3. 100 feet two 4/0 wires per leg in conduit	2.3
Total	10.8

Equivalent continuous thermal loading:
0.7×150 kva = 105
$0.1 \times 4 \times 20$ kva = 8

113 kva = 470 amperes at 240 volts

Example 2. Small Job-Welding Shop

Machines:
Three 50-kva spot welders
Two 150-kva press welders
One 200-kva projection welder

Maximum kilovolt-ampere load swing of largest machine:
2,100 amperes at 240 volts = 500 kva

Regulation for 500 kva:

	Per Cent
1. Supply system (4,800 volts)	4.1
2. 500-kva, single-phase, 4,800/240-volt, 3-per-cent, Z transformer	2.9
3. 150 feet one $^1/_4$-inch by 4-inch bar per leg, 1-inch centers	3.7
Total	10.6

Equivalent continuous thermal loading:
10 per cent $\times$ 650 kva = 65 kva = 270 amperes at 240 volts

Example 3. Small Manufacturing Plant

Machines:
Five 250-kva press welders
Two 50-kva spot welders
Eight 30-kva spot welders

Maximum kilovolt-ampere load swing of largest machine:
825 amperes at 485 volts = 400 kva

Regulation for 400 kva:

	Per Cent
1. Supply system (24,000 volts)	1.1
2. 700-kva, single-phase, 24,000/485-volt, 13-per-cent, Z transformers	7.4
3. 150 feet one $^1/_4$-inch by 2-inch bar per leg, $2^1/_4$-inch centers	2.0
Total	10.5

Equivalent continuous thermal loading:
Practically all three-cycle welding so use about five per cent of sum of connected load $0.05 \times 1{,}590$ kva = 80 kva = 165 amperes at 485 volts

Example 4. Small Manufacturing Plant

Machines:
Two 150-kva projection welders (automatic feed)
One 75-kva spot welder
One 50-kva spot welder
Eleven 25-kva portable welders

Maximum kilovolt-ampere load swing of largest machine:
850 amperes at 240 volts = 205 kva

Regulation for 205 kva:

	Per Cent
1. Supply system (4,800 volts)	2.7
2. 600-kva, three-phase, 4,800/240-volt, 5-per-cent, Z power transformer bank	3.4
3. 170 feet two 4/0 wires per leg in conduit	2.6
Total	8.7

Equivalent continuous thermal loading:
150-kva projection welder
2,000 welds per hour—3-cycle welds
Duty cycle = $(2{,}000 \times 3)/(60 \times 60 \times 60)$ = 2.77 per cent
200 kva at 2.77 per cent duty cycle = 34 kva continuous
Two machines = 2×34 = 68 kva continuous
Remaining machines, 10 per cent $\times$ 400 = 40 kva
Total, 108 kva

Example 5. Large Manufacturing Plant

Location *A*. Connect to Phase *AB*

Machines:
Three 550-kva butt welders
One 500-kva projection welder
One 400-kva projection welder
Three 150-kva projection welders

Maximum kilovolt-ampere load swing of largest machine:
2,700 amperes at 480 volts = 1,300 kva

Regulation for 1,300 kva:

	Per Cent
1. Supply system (4,800 volts)	5.6
2. Three 500-kva, single-phase, 4,800/480-volt, $3^1/_2$-per-cent, Z transformers	3.0
3. 125 feet two $^1/_4$-inch by 4-inch bars per leg, interlaced $2^1/_4$-inch centers	1.7
Total	10.3

Equivalent continuous thermal loading:
550-kva butt welder
200 welds per hour—30-cycle welds
Duty cycle = $(200 \times 30)/(60 \times 60 \times 60)$ = 2.77 per cent
1,300 kva at 2.77 per cent duty cycle = 216 kva continuous
Three machines = 3×216 = 648 kva continuous
Remaining machines, 10 per cent $\times$ 1,350 = 135 kva
Total, 783 kva = 1,670 amperes at 480 volts

Location *B*. Connect to Phase *BC*

Machines:
40 hydromatic welders, 150 to 300 kva each
Total connected load = 7,000 kva

Maximum kilovolt-ampere load swing of largest machine:
2,100 amperes at 480 volts = 1,000 kva

Regulation for 1,000 kva:

	Per Cent
1. Supply system (4,800 volts)	4.1
2. Two 500-kva, single-phase, 4,800/480-volt, $3^1/_2$-per-cent, Z transformers	3.5
3. 200 feet two $^1/_4$-inch by 4-inch bars per leg, interlaced $2^1/_4$-inch centers	1.9
Total	9.5

Equivalent continuous thermal loading:
15 per cent $\times$ 7,000 kva = 1,050 kva = 2,200 amperes at 480 volts

Location *C*. Connect to Phase *CA*

Machines:
Two 700-kva butt welders
Two 500-kva butt welders

Maximum kilovolt-ampere load swing of largest machine:
3,500 amperes at 480 volts = 1,670 kva

Regulation for 1,670 kva:

	Per Cent
1. Supply system (4,800 volts)	6.9
2. Three 500-kva, single-phase, 4,800/480-volt, $3^1/_2$-per-cent, Z transformers	4.0
3. 150 feet two double $^1/_4$-inch by 3-inch bars per leg, interlaced 3-inch centers	3.1
Total	14.0

The two 700-kva machines were interlocked so that they could not be operated together and the two 500-kva machines were also interlocked.

Equivalent continuous thermal loading:
700-kva welder
100 welds per hour—$2^1/_2$ second welds
Duty cycle = $(100 \times 2^1/_2 \times 60)/(60 \times 60 \times 60)$ = 6.95 per cent
1,670 kva at 6.95 per cent duty cycle = 440 kva
Two machines = 2×440 = 880 kva
500-kva welder
100 welds per hour—2 second welds
Duty cycle = $(100 \times 2 \times 60)/(60 \times 60 \times 60)$ = 5.55 per cent
1,200 kva at 5.55 per cent duty cycle = 283 kva
Two machines = 2×283 = 566 kva
Total, 880 + 566 = 1,446 kva

Reference

1. REACTANCE CHART FOR WELDER BUS PROBLEMS, R. C. Bouse and J. D. Scarbrough. *Electrical World*, volume 115, No. 10, March 8, 1941 page 106.

Discussion

Discussion will be found in the 1941 annual TRANSACTIONS volume and in the December 1941 SUPPLEMENT to ELECTRICAL ENGINEERING—TRANSACTIONS SECTION.

A Conserved-Pressure Air-Blast Circuit Breaker for High-Voltage Service

W. R. RANKIN
NONMEMBER AIEE

R. M. BENNETT
ASSOCIATE AIEE

Synopsis: This paper describes the design and construction of a 138-kv, 1,500,000-kva air-blast circuit breaker. The construction is made possible by the use of a new interrupting device which utilizes the axial blast nozzle together with a "conserved pressure" chamber. The chamber receives the exhaust from the interrupting nozzle and contains the movable contact of the breaker in its open position. By means of a spring-loaded relief valve the pressure and dielectric strength of the air in the chamber are maintained at a high level.

The pressure in the chamber is at the same time less than 50 per cent of the pressure above the nozzle restriction so that the air flow through the interrupting nozzle is unimpaired, being the same as through the same nozzle discharging to atmospheric pressure. As a consequence, the conserved pressure breaker is found to have the same ability to interrupt current as a conventional axial nozzle but to be capable of interrupting circuits of much higher voltage.

The 138-kv three-phase breaker consists of two interrupting units in series per pole with a disconnecting device included as part of the breaker. Operation of the breaker is entirely pneumatic, opening and closing being performed by energizing the electrically operated valve.

Interrupting Unit

Two distinct types of air-blast interrupting units have previously been described, the cross blast,[1,2,4] in which air is directed across the arc formed in the path of the separating contacts, and the axial blast in which air flows through an orifice in the direction of the moving contacts.

Data[1] published at the 1940 midwinter convention showed that the European axial blast unit required a volume of air for interruption that was proportional to the maximum current interrupted. As a consequence such a breaker would require excessive quantities of air if it were built in the ratings found in this country. The problem of interrupting these high currents, of as much as 100,000 amperes, was solved by the introduction of the cross-blast unit which makes very economical use of air.

For high-voltage service, however, the currents to be interrupted are relatively light and the interruption problem is one of voltage magnitude. Under these conditions, the axial nozzle shows more promise for it is naturally a better insulating structure than the cross-blast breaker. Since it is cylindrical it may be turned from a solid piece of insulating material and it can be readily accommodated inside of a porcelain insulator.

However, the straight axial nozzle was found to have limited voltage-interrupting capacity and it was through a study of these limits that the conserved pressure interrupter was developed. The conserved pressure breaker is a solution to the problem of interrupting relatively light currents at high voltage. Its development and a direct comparison between it and two axial nozzles will be described.

A simple form of the axial-blast interrupting unit which has been used in Europe is illustrated by figure 1. In this design high-pressure air flows around the cylindrical stationary contact and expands to the atmosphere through the nozzle from which the moving contact has been withdrawn. The moving contact is drawn out into the open air and in the fully open position comes to rest in a region of atmospheric pressure.

Figure 2 illustrates the variation of the dielectric strength of air as a function of pressure. As a consequence of this variation, the dielectric strength of the air at the fixed contact of the breaker is five or six times as great as at the moving contact whereas, depending upon the interrupter configuration, the voltage gradient in the low-pressure area may be as high as in the high-pressure region. As the voltage rises, after the current has been momentarily interrupted by the air blast, the moving contact then provides a starting point for an electrical breakdown between the contacts.

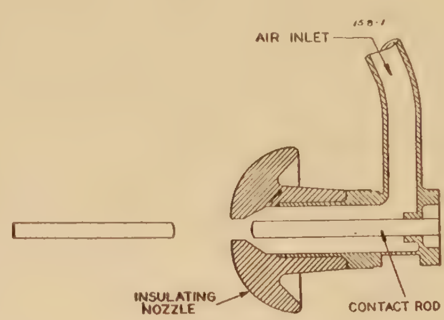


Figure 1. European high-voltage air-blast nozzle

This dielectric breakdown between the contacts can be avoided by a nozzle configuration of the type shown in figure 3*A*. Such a nozzle extends the region of high pressure—high dielectric-strength air to such a length that the contact spacing can withstand a high-applied voltage in spite of the fact that the air at the end of the moving contact is overstressed.

The interrupting ability of this long

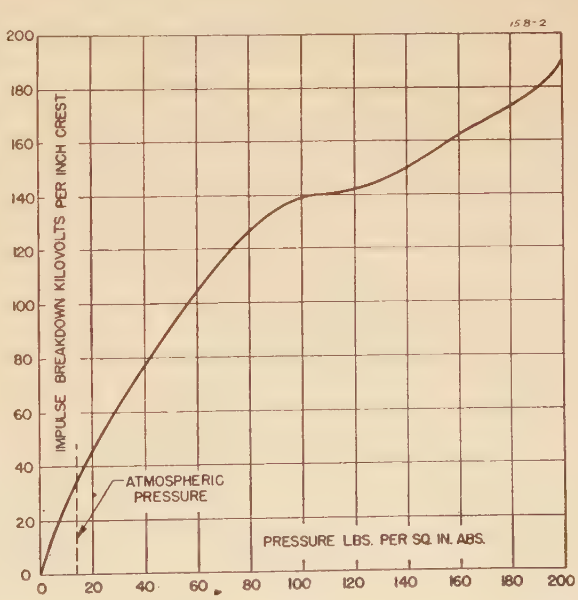
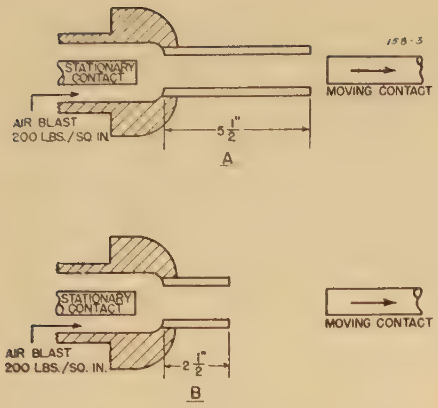


Figure 2. Impulse breakdown of a two-centimeter rod gap in air as a function of pressure. Temperature 25 degrees centigrade

Paper 41-58, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 28, 1940; made available for preprinting December 13, 1940.

R. M. Bennett is in the circuit breaker development division of the General Electric Company, Philadelphia, Pa.; W. R. Rankin is also employed by this company.

1. For all numbered references, see list at end of paper.



AXIAL NOZZLES

Figure 3. High-voltage air-blast nozzle. Inlet pressure 200 pounds per square inch

Exhaust pressure—atmospheric. Orifice diameter $1^1/_4$ inches

nozzle, in kilovolt-amperes, is plotted in figure 4 as a function of voltage. It is to be noted that although the breaker can interrupt a relatively large kilovolt-ampere at 38 kv, it has a definite current limit, so that, at lower voltages, where a larger current must be interrupted for a given kilovolt-ampere, the breaker fails. That is, the large volumes of ionized gas produced by large currents cannot be discharged by the long-restricted nozzle with sufficient rapidity to permit interruption.

The nozzle of figure 3*B* represents another extreme. It consists of little more than an orifice and is consequently capable of interrupting considerable current at low voltage. See figure 4. However, after interruption of the current at high voltages, progressive dielectric breakdown proceeds from the overstressed air at the tip of the moving contact back toward the orifice to such an extent that the high-pressure air becomes overstressed and it too breaks down.

These difficulties were overcome by the conserved pressure design which permits the moving contact to remain in a region of high-pressure air after the contacts have separated.

Figure 5 is a schematic representation of the breaker. High-pressure air is supplied from below, flows around the stationary contact and expands through an orifice to a chamber surrounding the moving contact. Pressure in this chamber is maintained at approximately 100 pounds per square inch by means of a spring-loaded relief valve. Provided the pressure in the chamber does not rise above approximately 53 per cent of the pressure above the orifice, the velocity and density of the air blast are unaffected by the pressure. It would therefore be expected that the performance of the conserved pressure breaker would be similar to that of the short orifice with the exception that it could interrupt much higher voltages. The dashed curve of figure 4 confirms this fact.

Breaker Construction

Each phase of the 138-kv air-blast circuit breaker consists of two conserved pressure-type interrupting units in series. The breaker which is rated 1,500,000 kva is supplied with air at 350 pounds per square inch.

The schematic drawing figure 6 shows the general arrangement of a single pole of the breaker. See figure 7. The essential parts consist of a main-blast valve for admitting air to the interrupters, an interrupting unit, a disconnect, and a mechanism for operating the disconnect.

The three-phase breaker has a main-air blast valve for each phase of the breaker. These are of the same type as the valves used in the 15-kv air-blast breakers described by Messrs. Strang and Boisseau at the 1940 midwinter AIEE convention.[3] They are poppet-type valves actuated by a piston which in turn is operated by air from a solenoid-operated differential pilot valve. The valves have an over-all operating time of two cycles from the time the solenoid coil is energized until the valve is completely open.

The interrupting contacts are separated by the action of the main air blast and are returned to the closed position by springs as soon as the air blast is turned off. Consequently a disconnect is provided, the function of which is to provide a clear air break after interruption is complete and before the interrupting contacts return to their closed position.

Closing of the breaker is performed by closing the disconnect. The closing speed of the breaker is not materially affected by current magnitudes in excess of the minimum breaker rating. This is accounted for by the fact that in the 138-kv breaker, the maximum rated current is a relatively light 9,500 amperes so that the magnetic forces are small compared with the inertia of the disconnect assembly.

The interrupting units are entirely pneumatic in operation, and require no mechanical connection with ground. The main air blast acts on a piston which is integral with the moving contact to move the upper contact upward separating the contacts.

When the movable contact has been withdrawn from the nozzle restriction the air blast which follows sweeps the contact space free of ionized gas at a current zero. The 138-kv breaker uses two interrupters in series, the total contact motion of each being eight inches. The interrupting contacts are returned by springs to the closed position as soon as the blast valve closes.

The interrupting nozzle is turned from a block of insulating material similar to fiber in possessing the property of becoming volatile at moderate temperatures. In the presence of an arc this property prevents the deposit of carbon on the surface of the nozzle and at the same time the gas which is evolved prevents the nozzle surface from reaching the high temperatures at which many otherwise

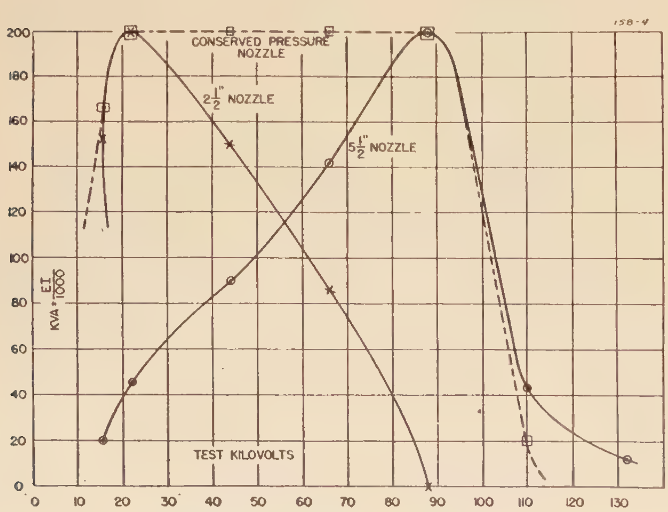


Figure 4. Interrupting ability of high-voltage air-blast nozzles. Inlet pressure 200 pounds per square inch. Maximum recovery rate 2,500 volts per microsecond

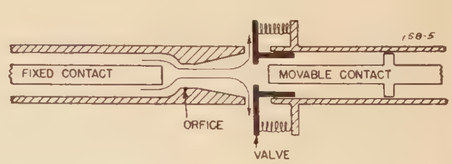


Figure 5. Schematic diagram of conserved pressure-interrupting unit

Inlet pressure 200 pounds per square inch. Orifice diameter $1^1/_4$ inches

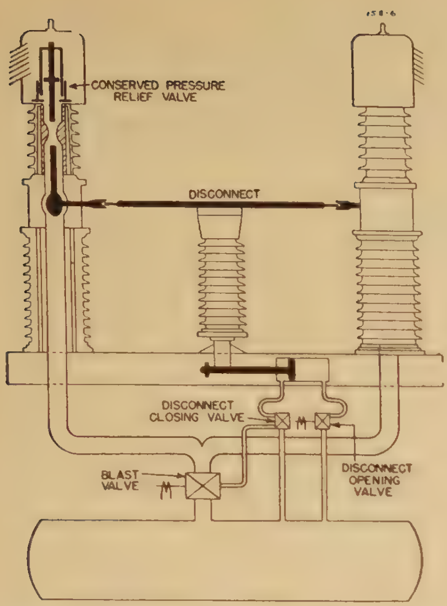


Figure 6. Schematic diagram of a single pole of the 138-kv, 1,500,000-kva air-blast circuit breaker

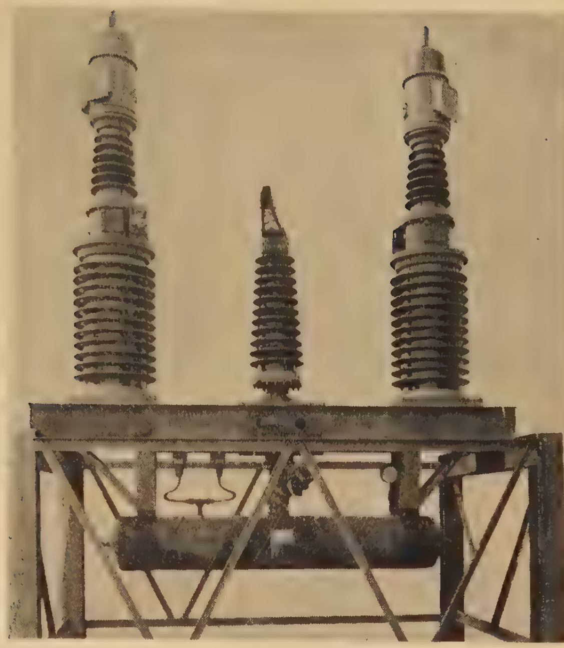


Figure 7. A single pole of the 138-kv, 1,500,000-kva air-blast circuit breaker

good insulators become conductors. The nozzle is contained in a herkolite tube which supports the upper contact piston and the conserved pressure-relief valve. The tube in turn is contained in a porcelain insulator.

The disconnect is also supported by a porcelain insulator which was specially developed for the purpose. The porcelain instead of having a straight creepage path inside, requiring that it be oil-filled and sealed, is made of a number of sections fused together. Each section is shaped like a cylinder closed at one end. When the sections are stacked up to form the insulator the closed ends of the sections become solid partitions across the inside of the insulator.

The disconnect arm engages long sliding stationary contacts by means of a

Table I. Single-Phase Opening and Closing-Opening Tests of AR-30-150, 138-Kv, 1,500,000-Kva Air-Blast Circuit Breaker

Test Number	Service	Single-Phase (Kilovolts)	RMS Amperes: Maximum Loop Closing	RMS Amperes: Initial in Arc	Trip Impulse to Interruption (Cycles)	Recovery Voltage: Rate of Rise	Recovery Voltage: Peak Value (Kilovolts)	Air Pressure in Tank
1	O	132		40	5.2	590	290	300
2	O	132		43	4.9	630	320	300
3	O	132		470	5.7	1,420	320	300
4	O	132		720	5.7	1,600	360	300
5	O	132		890	6.0	2,000	290	300
6	O	132		1,150	5.5	2,000	290	300
7	O	132		1,280	6.5	2,200	310	300
8	O	132		1,420	5.7	2,400	280	300
9	O	88		750	4.9	1,300	200	300
10	O	88		1,330	5.7	2,100	220	300
11	O	88		1,880	5.5	2,400	180	300
12	O	88		2,100	5.5	2,500	190	300
13	O	66		2,900	5.3	2,400	110	300
14	O	44		3,800	5.4	1,900	82	300
15	O	44		4,400	4.8	1,900	75	300
16	O	22		6,900	5.0	1,000	36	300
17	O	22		7,700	5.2	1,100	38	300
18	O	22		9,700	5.5	1,100	33	300
19	O	22		10,700	5.5	1,100	33	300
20	O	22		9,500	5.5	710	30	300
21	O	132		80	4.4	1,410	373	300
22	O	132		670	5.2	3,100	312	300
23	O	132		1,100	5.5	4,100	261	300
24	O	132		1,500	5.0	4,500	261	300
25	CO	132	61	61	4.5	430	230	350
26	CO	132	690	660	5.5	1,700	300	350
27	CO	132	1,180	970	5.0	1,900	240	350
28	CO	132	1,490	1,190	5.0	2,000	250	350
29	CO	132	1,810	1,390	5.2	2,100	240	350
30	CO	132	2,300	1,610	5.2	2,300	250	350
31	CO	88	84	84	4.3	780	210	300
32	CO	88	3,500	2,600	5.0	2,500	150	300
33	CO	88	5,300	3,600	5.0	2,500	192	300
34	CO	44	4,800	3,900	5.4	1,800	83	300
35	CO	44	4,900	4,300	4.7	1,800	74	300
36	CO	22	10,200	7,500	4.8	930	36	300
37	CO	22	11,300	8,100	4.7	980	37	300
38	CO	22	10,000	8,500	5.2	1,100	37	300
39	CO	22	13,600	9,500	5.2	1,000	33	300

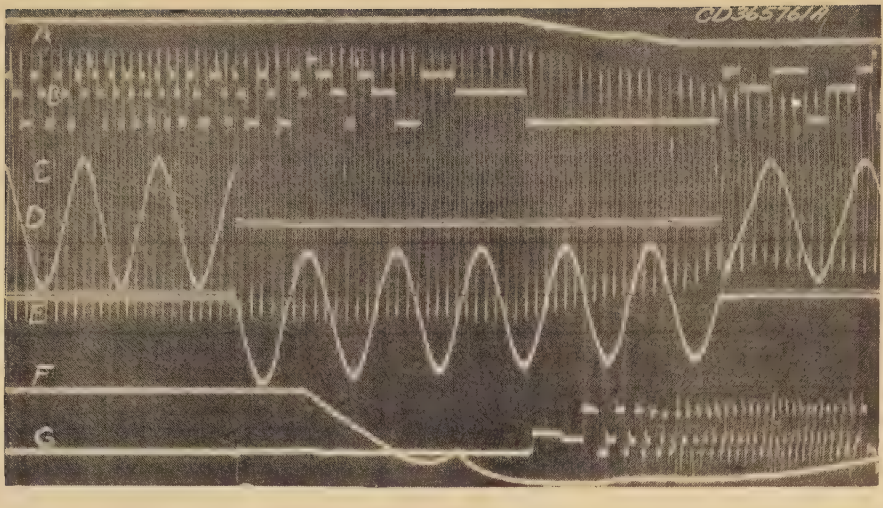


Figure 8. Test number 30. Table I. Single-phase closing-opening operation at 132 kv

Curve *A*—Disconnect trip impulse
Curve *B*—Disconnect travel—0.67 inch per step
Curve *C*—Pressure in interrupting chamber
Curve *D*—Voltage at breaker terminals
Curve *E*—Current through breaker
Curve *F*—Air-blast trip-coil current
Curve *G*—Interrupting contact travel—0.1 inch per step

loose-hinged blade which twists as it disengages. The contacts are so shaped that the arc formed during closing burns heavy contact tips rather than the contact surfaces. Both opening and closing of the disconnect is performed by a double-ended pneumatic piston which acts to rotate, about a vertical axis, the whole assembly, consisting of disconnect arm and insulator.

Air Auxiliaries

Air is supplied to the breaker tank from a conventional electric motor-driven storage and compressor unit. To eliminate the possibility of moisture reaching the breaker a compression cycle is used to dry the air.

Air is compressed to 1,000 pounds per square inch, cooled so that moisture is condensed in the high-pressure chamber, and is expanded to 350 pounds per square inch. After expansion the dew point of the air is approximately 80 degrees Fahrenheit below the temperature of the ambient air.

The control for the expansion valves is by means of Bourdon-type pressure switches. The control is arranged so that no air expands from the 1,000-pound tank to the 350-pound tank unless the compressor has brought the high-pressure tank up to full pressure. Thus no air can flow into the 350-pound tank unless it has gone through the complete compression cycle.

Operation

A breaker-opening operation is performed by electrically energizing the three-blast valve solenoids in parallel. The three valves are pneumatically interconnected so that all three main blast valves can be opened by any one of the solenoid-operated pilot valves. Opening of the blast valves initiates two functions. First, an air blast is supplied to the interrupting units to separate the contacts and interrupt the arc. Second, air is supplied to the disconnect control to initiate opening of the disconnects. The disconnect control is pneumatically interlocked with the blast valves so that the disconnect cannot operate unless all three blast valves have opened. If all three blast valves open, air is admitted to a differentially-operated pilot valve which in turn admits air directly from the tank to the disconnect operating piston. Separation of the disconnect contacts is timed to take place after the arc has been interrupted. Once the opening operation has been initiated the closing control solenoid is electrically disconnected. Electrical control is also provided so that the disconnect operation can be prevented.

A Bourdon-type pressure switch is used to open both the electrical opening and closing circuits in case the tank pressure is below the safe operating limit. Breaker closing is performed by electrically energizing a valve which admits air to the closing side of the disconnect operating piston.

Rapid reclosing is provided as indicated by figure 9. The disconnect opening pilot valve is a three-way valve which in the energized position admits air from the tank through a dump valve to the opening side of the operating piston. A light spring together with air flowing through the dump valve in the direction of the operating cylinder holds the dump valve closed.

When the pilot valve is de-energized, however, it opens a passage, from the back of the dump valve to the atmosphere, permitting the dump valve to open and exhaust the air from the opening side of the disconnect operating piston. Trip-free operation is provided by using the same valve arrangement for the closing side of the disconnect.

A complete closing-opening operation of the breaker takes place in the following order. Starting with the interrupting contacts closed and the disconnect open,

1. Disconnect solenoid energized.
2. Disconnect closes.
3. Disconnect solenoid de-energized.
4. Blast-valve solenoid energized.
5. Blast valve opens.
6. Disconnect opening pilot energized by air blast.
7. Interrupting contacts parted by air blast and arc interrupted.
8. Disconnect opens.
9. Blast valve de-energized.
10. Interrupting contacts return to closed position.

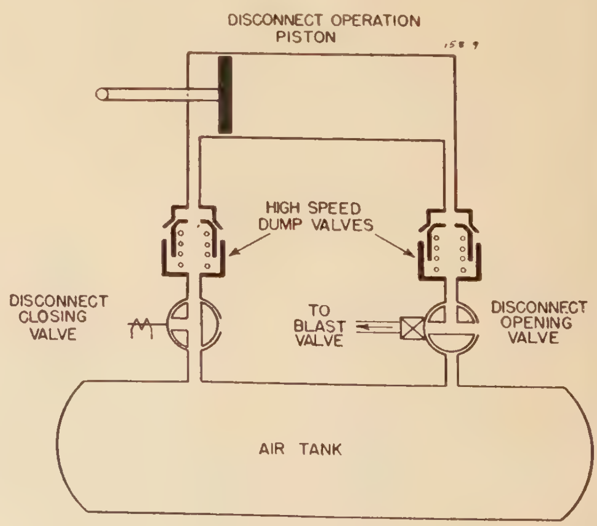


Figure 9. Disconnect operating mechanism

A New Air Circuit Breaker With 250,000-Kva Interrupting Capacity

R. C. DICKINSON
ASSOCIATE AIEE

R. H. NAU
ASSOCIATE AIEE

Synopsis: Heretofore it has not been commercially feasible to apply air-type breakers of the 5,000-volt class to circuits capable of producing short-circuit currents equivalent to 250,000 kva. However the continued demand for air circuit breakers of higher interrupting ratings has stimulated the development of a new breaker suitable for these applications. This achievement has been accomplished through magnetically enhanced diffusion of ionized particles, establishing dielectric strength in a gaseous region which was previously highly conducting. The interrupter consists essentially of an arc chamber of laterally spaced refractory plates embodying V-shaped slots and a magnetic circuit which imposes an intense magnetic field transverse to the slotted plates during the arcing period.

The theory of arc interruption by this new air breaker is considered. Design details are described and illustrated. Complete sets of test results are given, with representative oscillograms. The test results are discussed, and it is demonstrated that the new breaker is applicable to modern metal-clad switchgear.

I. Introduction

THE advantages of air-type power switching equipment are becoming increasingly apparent to the electrical industry. The result is a general desire to be able to supply air circuit breakers over the entire range of applications which have become established by the use of oil-type switching equipment. In response to the demand to fill in the gaps in the established interrupting ratings with air circuit breakers, a new self-contained unit suitable for an interrupting rating of 250,000 kva at five kv has been developed.

Early in 1938 development of principles somewhat different from those of the original "De-ion" air breakers[1] resulted in devices having very high-current interrupting ability at moderate voltages.[2] Currents as high as 120,000 amperes at 750 volts were interrupted. The principle of operation is a combination of arc construction and rapid gas motion. The gas motion is produced by virtue of a self-induced magnetic field which imparts a net upward component of velocity to the conducting electrons. The arcing time is definitely limited to one-half cycle or less.

The scope of this principle of magnetic deionization was expanded to devices having 150,000-kva interrupting ratings at 2,500 and 5,000 volts.[3] Continuation of the development has resulted in still further application of magnetically enhanced diffusion of ionized particles. The following sections are devoted to describing the newly developed air circuit breaker having an interrupting rating of 250,000 kva at 4,000 to 5,000 volts.

Paper 41-32, recommended by the AIEE committee on protective devices and presented at the AIEE winter convention, Philadelphia, Pa., January 27-31, 1941. Manuscript submitted November 25, 1940; made available for preprinting December 6, 1940.

R. C. Dickinson is circuit-breaker engineer and R. H. Nau development and design engineer for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

1. For all numbered references, see list at end of paper.

II. Design of the Interrupter

In addition to meeting the current carrying and interrupting requirements, an air circuit breaker should have a space factor comparable to the similarly rated oil breaker. The problem is then one of suitably drawing and enclosing the arc and controlling the ionized gases and other by-products of arc interruption. It has been found that definite advantages exist in utilizing a relatively short arc and permitting the current of the arc in interruption to go to its normal zero in cycle—whereat intensive deionization is provided to establish dielectric strength. The method of magnetic deionization possesses this type of arc characteristic.[3]

An extended series of tests, table I, made on a standard 150,000-kva 5,000-volt breaker demonstrated that there was a wide margin of safety above the 150,000-kva rating. Hence the logical program was to continue development of this design.

It had been indicated that the voltage which could be interrupted was very nearly proportional to the number of refractory plates in the arc chamber. Further, the amount of current that could be interrupted was a function of the plate width and thickness and of the vent space between the plates. Hence for the five-kilovolt ratings, two refractory sections or twice the number of insulating plates were necessary. In order to bring the arc uniformly into the V-shaped slots of all the plates the structure was supported at sufficient height above the arcing contacts to permit the use of sloping arc horns. See figure 1. The added arc length and distance of arc travel required greater venting to exhaust and deionize the hot gases. The vents between the refractory plates were made more effective by using wider and longer plates and by stacking them farther apart. A space was provided intermediate to the two refractory sections to release the initial gas pressure and to stabilize the arc during current interruption. Figure 2 is a picture of the two sections of refractory plates taken from a 250,000-kva 5-kv arc chamber.

During short-circuit operation of the magnetic "De-ion" breaker an arc is drawn between the separating arcing contacts, and is looped upward, magnetically, into the V-shaped slots. By transfer of the arc to the panel-end horn (figure 1),

Interrupting Tests

The 138-kv, 1,500,000-kva breaker is required to interrupt 6,300 amperes at rated voltage which is approximately 80 kv line to neutral. The maximum current rating is 9,500 amperes.

Table I is a series of single-phase interrupting tests performed on a single pole of the breaker. The currents interrupted range from light currents, similar to line-charging currents, to a maximum of 10,700 amperes.

Rates of rise of recovery voltage up to 4,500 volts per microsecond have been interrupted at 132 kv.

Figure 8 is a magnetic oscillogram of the closing-opening operation of test number 30.

References

1. The Cross-Air-Blast Circuit Breaker, D. C. Prince, J. A. Henley, and W. K. Rankin. AIEE Transactions, volume 59, 1940 (September section), pages 510–17.

2. A New 15-Kv Pneumatic Circuit Interrupter, L. R. Ludwig, H. L. Rawlins, and B. P. Baker. AIEE Transactions, volume 59, 1940 (September section), pages 528–33.

3. Design and Construction of High-Capacity Air-Blast Circuit Breakers, H. E. Strang and A. C. Boisseau. AIEE Transactions, volume 59, 1940 (September section), pages 522–7.

4. Medium-Capacity Air-Blast Circuit Breakers for Metal-Clad Switchgear, R. M. Bennett and B. W. Wyman. AIEE Transactions, volume 60, 1941.

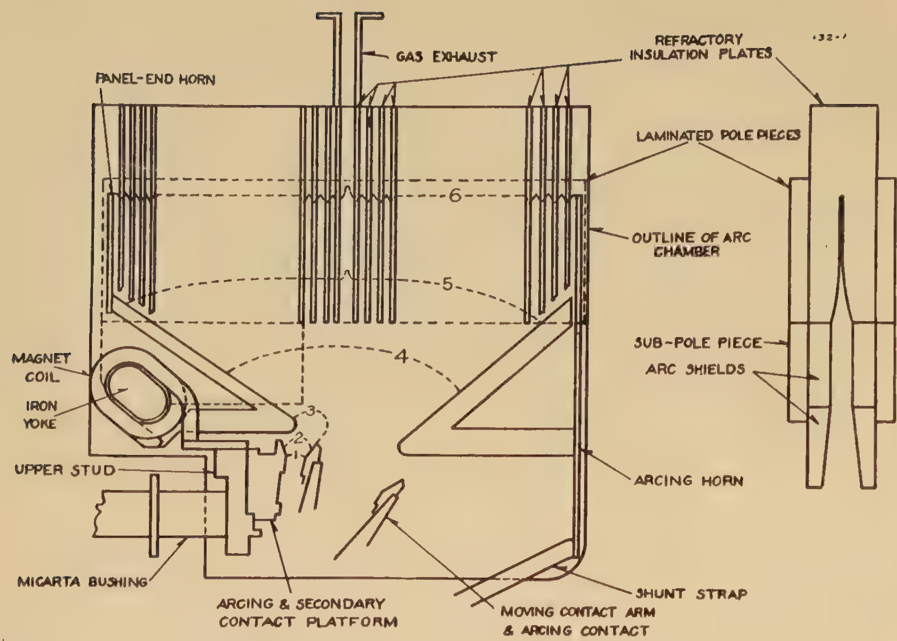


Figure 1. A diagrammatic sketch showing partial sections of the 5,000-volt magnetic "De-ion" interrupter. The dotted lines 1, 2, 3, 4, 5, and 6 indicate progressive positions in arc interruption

the magnet coil is switched into the circuit, thus imposing a strong transverse magnetic field. The upward motion of the arc is impeded by the refractory plates; however, a net upward component of velocity is imparted to the conducting electrons. They in turn bombard gas particles and produce a rapid flow of gas perpendicular to the arc. This reaction enhances the diffusion of the ionized gas particles and continuously causes the arc to ionize fresh gas in considerable quantities. The deionizing action is particularly prevalent near the edges of plates, and it continues in a sufficient degree to establish high dielectric strength during the period of relative low recovery voltage following a current zero.

By this method of magnetically enhanced diffusion of ionized gas particles the effectiveness and life of the interrupter are preserved. The long series of tests listed in tables II and III are typical runs which have not produced excessive wear on either the arc chamber plates or breaker contacts.

Figure 2. Two ceramic sections taken from an arc chamber after a series of 19 interrupting tests at 3,830 volts restored, single phase, and currents equivalent to 192,000 to 306,000 kva three phase

III. The Breaker Mechanism

The contact system and electromagnetic operating mechanism of the magnetic "De-ion" breakers are specially designed for high speed. Fast operation promotes both better contact protection and one-half cycle arcing time for currents of short-circuit values. Low inertia of the movable contact is obtained by a pivotally mounted contact arm upon which a pair of secondary and arcing contacts are rigidly attached to protect the main contact member. This main contact member is a solid copper block having heavy silver-inlay contacts. The arcing and secondary contacts are a silver-tungsten cintered mixture which is highly resistant to arcing. Figure 3 is a picture of a beaker with its contacts in open position.

A standard three-pole 5,000-volt breaker is shown in figure 4. The barrier structure is a plain interphase arrangement pivotally mounted as a unit at the

Figure 3. A 5-kv 2,000-ampere magnetic "De-ion" breaker with the unit interphase barrier and left-pole arc chamber removed to show the contacts and magnet coil

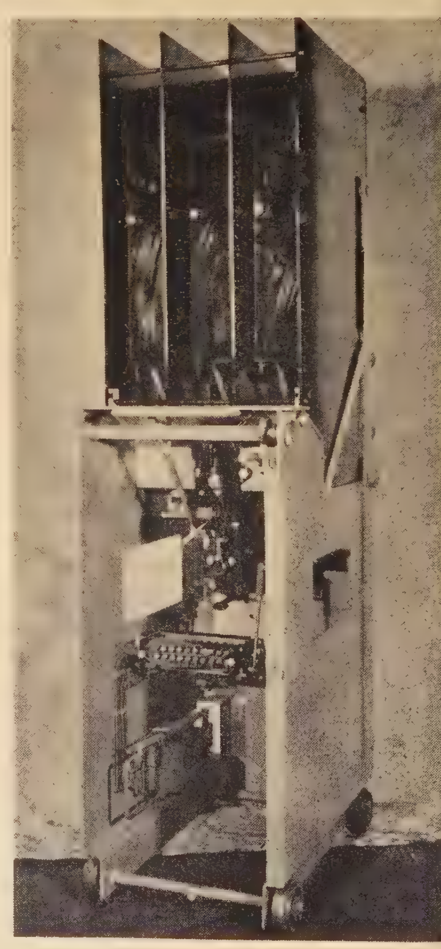


Figure 4. Complete draw-out type of magnetic "De-ion" breaker for five-kilovolt service

lower front corner. The unit is simply removed by pulling the top forward and lifting the assembly from its pivots.

The arc chambers are removable units supported by the laminated pole pieces. An individual chute assembly is shown in figure 5. The connectors of the arcing horns are automatically engaged when the arc chamber is pushed back into position on the laminated pole pieces.

The trip-free operating mechanism is mounted in a horizontal position immediately below the lower studs and moving contacts. It is isolated from the live parts by a steel barrier, and actuates the contacts through suitable insulating push rods. See figure 3.

Figure 5. The arc-chamber unit of a magnetic "De-ion" breaker

An air dashpot is directly coupled to the operating lever of the mechanism. The volume of air handled is sufficient to absorb the kinetic energy of the opening contacts at both no-load and short-circuit capacity, thus bringing the contacts to a gentle rest without impairing the opening speed for approximately 50 per cent of the contact travel. The air dashpot is clearly shown in figure 4.

The magnetic "De-ion" breaker is designed to meet the requirements of modern metal-clad switchgear. Figure 6 illustrates the standard arrangement of the entire line of magnetic "De-ion" breakers for 2.5 to 5 kv, 600 to 2,000 amperes and up to 250,000-kva interrupting rating at 5 kv. The width of the 100,000- and 150,000-kva 3-pole breakers is $21^3/_8$ inches, and that of the 250,000-kva 5-kv unit is 31 inches.

Figure 6. Horizontal draw-out metal enclosed switchgear unit with a magnetic "De-ion" breaker for 2.5 to 5 kv, 600 to 2,000 amperes and up to 250,000-kva interrupting rating

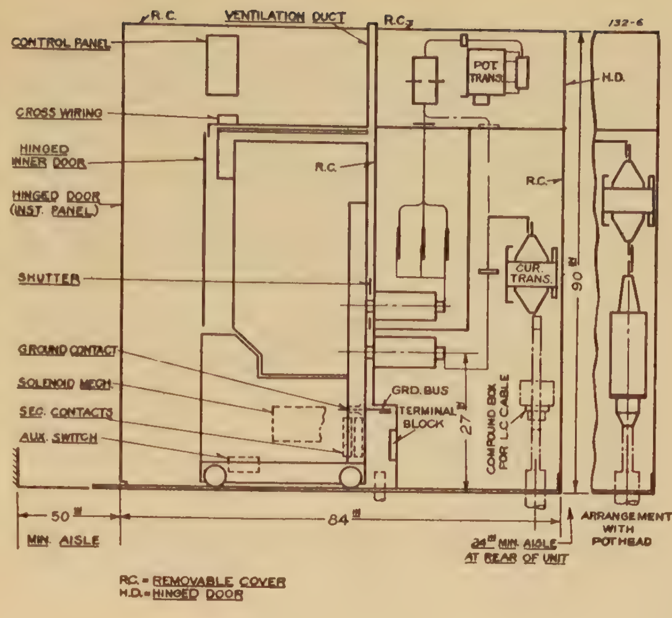
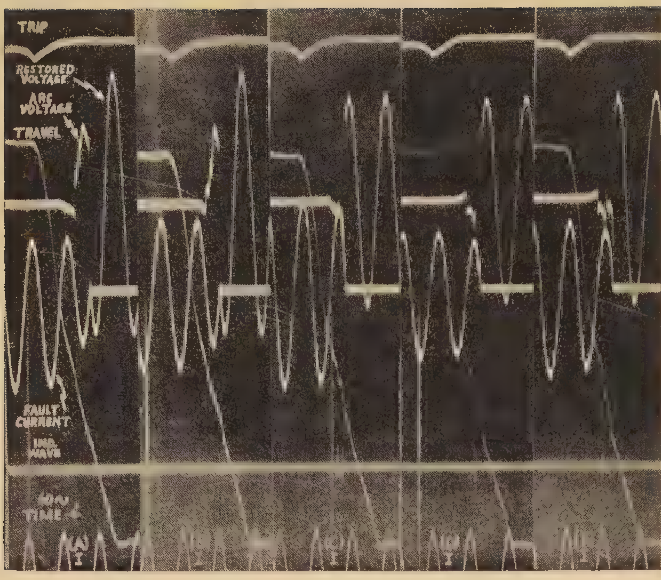


Table I. Typical Data From Interrupting Tests on a Single Pole of a 5,000-Volt 150,000-Kva Magnetic "De-ion" Breaker

Test Number	Test Voltage	RMS Amp. Interrupted	Arcing Time Cycles	Equivalent 3-ϕ Mva
1	3,300	27,000	1/2	154
2	3,500	28,500	1/2+	173
3	3,700	19,200	1/2	123
4	3,900	17,500	1/2−	118
5	4,100	18,600	1/2	132
6	4,300	25,000	1/2	186
7	4,500	18,600	1/2	145
8	4,700	19,400	1/2	158
9	3,000	10,000	1/2	52
10	4,900	18,000	1/2−	152
11	4,900	15,300	1/2	130
12	4,900	16,700	1/2−	142
13	5,000	16,000	1/2	139
14	5,000	600	4	
15	5,000	550	4	
16	5,000	380	5	
17	5,000	400	5	
18	5,000	360	5	
19	3,000	13,300	1/2	69
20	3,500	13,900	1/2−	84
21	4,000	13,300	1/2	92
22	4,300	16,500	1/2	123
23	4,500	14,500	1/2	113
24	4,700	15,800	1/2−	128
25	4,900	17,800	1/2	151
26*	5,000	16,800	3/4	146
27	5,000	18,600	1/2+	161
28*	5,000	16,000	1/2	139
29	5,000	16,000	1/2−	139
30	5,000	19,000	1/2	165
31	5,000	20,000	1/2+	173
32	5,000	19,400	1/2	168
33	4,000	19,400	1/2−	134
34*	4,000	18,800	1/2−	130
35*	4,000	20,500	1/2	144
36	4,000	22,600	1/2+	157
37	4,000	26,000	1/2	180
38	4,000	30,500	1/2−	211
39	4,000	26,500	1/2+	184
40	4,000	24,000	1/2−	166
41	4,000	26,000	1/2+	180
42	4,000	33,500	1/2	232
43	4,000	21,800	1/2−	151
44	4,000	23,500	1/2	163
45	4,000	30,500	1/2−	211
46	4,000	26,500	1/2	184
47*	4,000	24,000	1/2	166
48	4,200	37,000	1/2	269
49	4,200	31,300	1/2+	228

*Oscillograms of these tests are shown in figure 7.



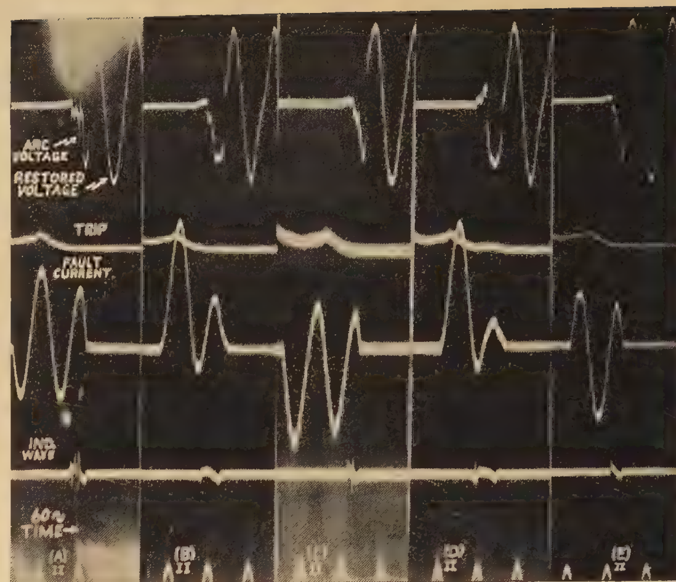
Current interrupted, amperes

16,800 | 16,000 | 18,800 | 20,500 | 24,000

Restored volts

4,600 | 4,700 | 3,750 | 3,640 | 3,800

Figure 7. Representative oscillograms of tests listed in table I



Current interrupted, amperes

24,800 | 39,900 | 25,900 | 36,800 | 25,900

Restored volts

3,830 | 3,800 | 3,830 | 3,890 | 3,950

Figure 8. Representative oscillograms of tests listed in table II

IV. Test Results

Extended series of tests were made during the development of the 250,000-kva 5-kv magnetic "De-ion" breaker. In addition to demonstrating ample margin for an interrupting rating of 250,000-kva at 5 kv, these numerous tests have shown the continued effectiveness of the breaker when applied to repetitious duty at and above the interrupting rating. Indeed, the wear on the contacts and arc chamber parts is small even after many operations, and the functioning of the breaker is in no way impaired.

Table I illustrates a typical run of 49 consecutive interrupting tests made on a single pole of a 5-kv 150,000-kva breaker without service to the breaker or arc chamber. The short-circuit values ranged from load currents to 37,000 amperes (equivalent to 291,000 kva, 3-phase). Figure 7 is a picture of five oscillograms taken from the tests listed in table I.

A short run of 19 interrupting tests with currents as high as 306,000 kva is indicated in table II. Figure 8 shows representative oscillograms from the group. These tests were made on a 5-kv 250,000-kva breaker, causing very little wear upon the arc chamber parts. The two individual ceramic sections of this chute are shown in figure 2.

A series of 34 short-circuit tests were made on a similar 5-kv 250,000-kva arc chamber. These tests are listed in table III, and the starred data are illustrated by the oscillograms of figure 9. The data indicate considerable margin above the interrupting rating of 250,000 kva.

During another series of tests on a single pole of a 5-kv 250,000-kva breaker two consecutive shots of 300,000 kva 3-phase were obtained. The severity of these interruptions did not stress the interrupter unduly. The oscillograms are shown in figure 10.

Numerous interrupting tests have been made at lower current values with five kilovolts across a single pole. These low currents were obtained by connecting an air-cored reactor of negligible resistance directly in series with the breaker and a 20,000-kva generator. At 1.6 amperes the arc was interrupted in less than one-half cycle. The arcing time-current characteristic rises gradually to about 22 cycles at 14 to 20 amperes and recedes to 4 cycles at 600 amperes. At currents above several thousand amperes the arcing time is only one-half cycle.

The magnetic "De-ion" breaker is applicable to circuits requiring repetitious switching. No-load *CO* life tests have been made in excess of 25,000 operations without repair to any part. At the close of the tests there was no indication of wear or strain on the breaker which would require overhauling or replacement of any major item.

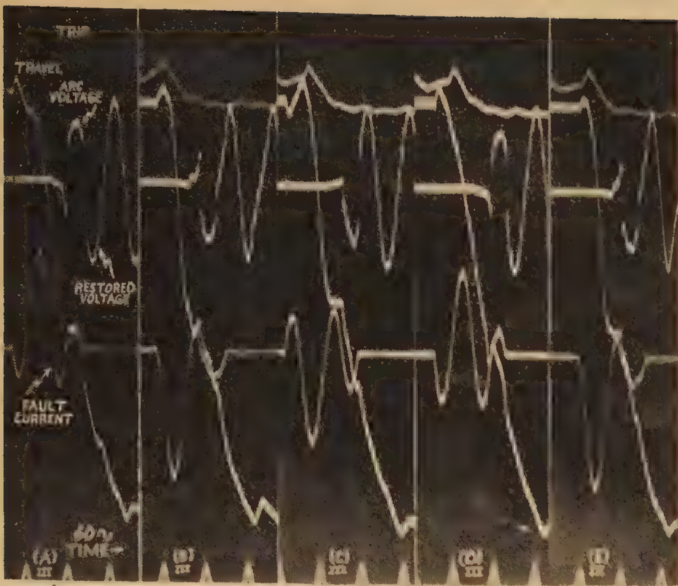
Table II. Typical Data From Interrupting Tests on a Single Pole of a 5,000-Volt 250,000-Kva Magnetic "De-ion" Breaker

Test Number	Test Voltage	RMS Amp. Interrupted (Thousands)	Arcing Time Cycles	Equivalent 3-ϕ Mva
1	4,000	29.0	1/2−	201
2	4,300	33.6	1/2	250
3	4,300	35.0	1/2+	261
4	4,300	28.0	1/2	209
5	4,300	31.2	1/2−	232
6	4,300	24.8	1/2	185
7	4,300	37.8	1/2−	282
8*	4,300	24.8	1/2	185
9	4,300	27.4	1/2	204
10*	4,300	39.9	1/2+	297
11	4,300	24.8	1/2+	185
12	4,300	24.8	1/2	185
13	4,300	26.4	1/2+	197
14*	4,300	25.9	1/2−	193
15*	4,300	36.8	1/2+	274
16	4,300	27.4	3/4	204
17	4,300	26.4	3/4	197
18	4,300	27.4	1/2−	204
19*	4,300	25.9	1/2−	193

*Oscillograms of these tests are shown in figure 8.

V. Conclusions

The principle of magnetically enhanced diffusion of ionized particles for establish-



Current interrupted, amperes

31,000 40,300 28,400 29,400 41,300

Restored volts

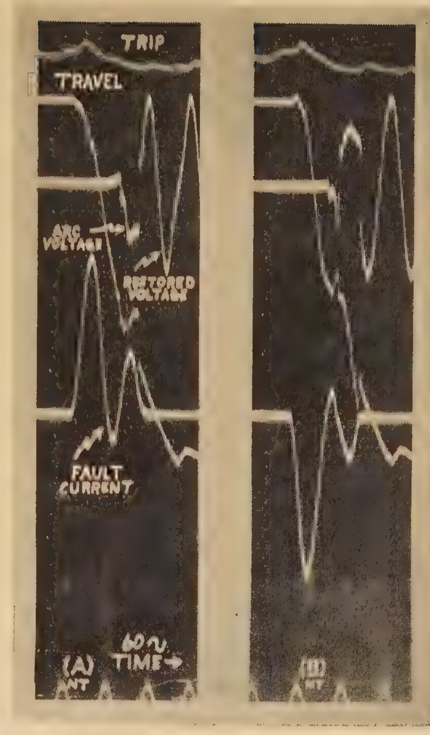
4,030 3,800 4,000 4,150 3,920

Figure 9. Oscillograms of tests indicated in table III

Table III. Extended Series of Interrupting Tests on a Single Pole of a 5,000-Volt 250,000-Kva Magnetic "De-ion" Breaker

Test Number	Test Voltage	RMS Amp. Interrupted (Thousands)	Arcing Time Cycles	Equivalent 3-ϕ Mva
1	4,000	36.2	3/4	250
2	4,300	41.3	1/2−	308
3*	4,300	31.0	3/4	231
4	4,300	32.6	1/2−	243
5	4,300	29.0	3/4	216
6	4,300	33.6	3/4	250
7	4,300	37.2	3/4	277
8	4,300	38.8	3/4	290
9	4,300	33.1	1/2−	247
10	4,300	26.9	3/4	200
11	4,300	24.8	1/2	185
12	4,300	25.8	1/2−	194
13	4,300	23.3	1/2+	174
14	4,300	31.0	3/4	231
15	4,300	25.8	3/4	192
16	4,300	41.3	1/2+	308
17	4,300	33.6	3/4	250
18	4,300	40.3	1/2−	301
19	4,300	31.0	1/2−	231
20*	4,300	40.3	3/4	301
21	4,300	28.4	1 −	212
22	4,300	28.4	1	212
23	4,300	24.3	1/2	181
24	4,300	30.0	1/2−	224
25	4,300	36.2	1/2−	270
26	4,300	39.8	1 −	295
27	4,300	29.5	3/4	220
28	4,300	37.2	1/2−	277
29*	4,300	28.4	1/2+	212
30	4,300	41.3	1/2−	308
31*	4,300	29.4	3/4	219
32	4,300	31.0	1−	231
33	4,300	28.4	1/2	212
34*	4,300	41.3	3/4	308

*Oscillograms of these tests are shown in figure 9.



Current interrupted, amperes

40,000 40,000

Restored volts

4,020 4,020

Figure 10. Two consecutive high-current interruptions obtained with a 5-kv 250,000-kva magnetic "De-ion" breaker

ing dielectric strength in a previously high conducting region has been successfully applied to an air circuit breaker. Extended series of interrupting tests with currents as high as 40,000 amperes and restored circuit voltages of 4,020 volts across a single pole indicate a conservative interrupting rating of 250,000 kva. The magnetic "De-ion" air circuit breaker is suitable for severe repetitious duty, and also meets the requirements of modern metal-clad switchgear.

References

1. Theory of the "De-ion" Circuit Breaker, J. Slepian. AIEE Transactions, volume 48, 1929, page 523.

2. A New High-Capacity Air Breaker, L. R. Ludwig and G. G. Grissinger. AIEE Transactions, volume 58 (August section), 1939, page 414.

3. Magnetic "De-ion" Air Breaker for 2,500–5,000 Volts, L. R. Ludwig and R. H. Nau. AIEE Transactions, volume 59 (September section), 1940, page 518.

Magnetic Fields in Watt-Hour Meters

Effects of Wave Form on the Registration of Single-Phase Watt-Hour Meters

C. A. KEENER
MEMBER AIEE

M. A. FAUCETT
MEMBER AIEE

M. S. HELM
NONMEMBER AIEE

Synopsis: The growing use of electrical equipment which causes distortion in the supply voltage and current has caused increased concern regarding the performance of watt-hour meters used to meter the energy required by such equipment. The watt-hour meter is designed and adjusted, in practice, to operate on practically distortionless current and voltage.

An analysis of the factors involved and an experimental study of meter registration under definitely controlled conditions show that watt-hour meters should perform satisfactorily unless the degree of distortion is large. These controlled conditions included wide variations in the distortion of potential and current both individually and together. The characteristics of meters of recent design, of all the major manufacturers, were studied experimentally.

Introduction

THIS study of the effects of variation in wave form on the registration of a watt-hour meter is a part of a general study of the magnetic conditions which exist in such meters during their operation. Data which are presented for illustration of these effects are to be considered more qualitatively than quantitatively since they apply directly to particular types of meters of recent design. The order of magnitude of the effects of variations in wave form can be inferred in any case except perhaps for meters of very early design.

Single-phase meters only are considered here. The influence of the interaction of the several elements of polyphase meters is to complicate relationships introduced by a variation in wave form and depends upon the position of the elements relative to each other. Since the general effect of harmonics is found to be small, the relatively small influence of one element on another in a multidisk meter should give rise to effects of but minor importance so far as they are caused by harmonics.

Because of the necessary differences between the designs of elements of multidisk and single-disk polyphase meters, the effects of wave-form variations on the performance of single-disk meters are being given separate study.

Meters of recent designs, although made by various manufacturers are much more nearly alike, fundamentally, in their magnetic circuits than those formerly manufactured. Many differences in detail are still present and although the net result is, in each case, a meter with satisfactory performance characteristics, variations may be noted in the performances of the meters when used in circuits where abnormal wave forms occur in voltage or current.

In addition to differences in the proportions of parts of the magnetic circuits of the meters, design details which influence the flux distribution and variation in a meter and consequently the performance characteristics under abnormal loads are the lagging circuit and the compensations for friction, temperature change, and overload. No attempt is made to evaluate separately the influence of each component part, their collective influence only being noted. Even with meters of the same design, differences among them which are not evident under normal conditions may become noticeable under abnormal conditions.

Discussion

The operation of a watt-hour meter depends upon the interaction of the fluxes produced by the component magnetomotive forces of the potential and current elements and the disk currents produced by the changing of those fluxes. The changes in these fluxes may be in either magnitude or position or both. The distribution of these fluxes in the meter and their variations in magnitude with time are important factors in the determination of the disk torque upon which the meter registration depends. Differences in both the space distribution of the fluxes with time for the various meters are determined to a large degree by the differences in the details in the designs of the meters. Although the details of element design have some influence, the time variation of the flux is determined largely by the external conditions in the circuit. The design of the magnetic circuit, with associated electrical circuits, practically determines the space distribution of the flux. Because of the variable timing of the magnetomotive forces of the potential and current elements the space distribution of their resultant flux is variable and hence is a function of external conditions as well as the magnetic design. In a like manner, the time variation of the resultant flux depends upon the variations in magnetic reluctance introduced by the magnetic design as well as the magnetomotive force variation dictated by external conditions. The materials of construction and their physical properties will have marked influences on the flux and hence on the characteristics of the meter.

It is the purpose, here, to discuss the effects of variations in the wave form of current and voltage, as fixed externally, on the registration of watt-hour meters.

Generally, the net conditions existing in and around any circuit where currents and voltage are nonsinusoidal can be considered to depend upon all components, fundamental and harmonics, present. This dependence may be difficult to determine unless linear relations exist. However, in most instances in power circuits, if harmonics are present to an important degree it is because of nonlinear response of iron in magnetic circuits to magnetization. In such cases the third and fifth harmonics are usually most prominent and except in instances of very high magnetic densities are the only ones of importance. Frequently only the third harmonic is sufficiently large to have much influence. For this reason, an experimental study of the effects of one major harmonic (the third) should give an understanding of the effects to be expected in practical cases.

In any case, net meter-disk torque should be produced only when voltage and current of the same frequency are used because in such cases only is there a net transfer of energy. This applies to harmonic components as well as to the fundamental. Experimentally it has been found that this is not true in all cases with practical meters. Net torque is produced even though voltages and currents of different frequencies are used. However, a distinction must be made between potentials and currents and the meter fluxes that result from them. The presence of iron in the magnetic circuits of the meters with its nonlinear response

Paper 41-43, recommended by the AIEE committee on instruments and measurements and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted October 28, 1940; made available for preprinting December 11, 1940.

C. A. Keener is associate professor of electrical engineering, M. A. Faucett assistant professor of electrical engineering, and M. S. Helm instructor in electrical engineering, all at the University of Illinois, Urbana.

to magnetizing forces will give rise to time variations in the fluxes of harmonics which are not present in the magnetizing forces. These harmonics may give rise to torque components which with reference to the torque produced by the fundamentals may be positive or negative. Figures 2–5 are reproductions of oscillograms showing the presence of such harmonics in the variation of the air-gap flux in a representative meter of recent design with only fundamental potential and current variations.

In certain single-phase watt-hour meters the cores of the current and potential elements are placed as shown in figure 1 relative to the disk. The points indicated along a center line of these cores designate positions at which the rates of variation of flux density are shown in figures 2, 3, 4, and 5. These rates of variation are for conditions specified and correspond to actual conditions of operation with sine waves of potential and current.

It will be noted that with sinusoidal potential impressed alone (figure 2), that the variations at all points approximate the sinusoidal. A careful analysis of these variations, however, shows that several harmonic components of small magnitude are present. The magnitudes at the various points differ widely. These conditions are to be expected since the flux linkages with the potential coil windings must vary in such a manner as to produce an induced voltage differing from the (sinusoidal) impressed voltage by only the resistance drop. This, with an iron core, requires that the induced voltage (and hence variation of flux) must contain harmonic components because of the harmonic content of the exciting current. These flux harmonics are of small magnitude relative to the fundamental as the curves of figure 2 indicate. The variations in amplitudes among the points are a result of the distribution of core material.

For the condition of the current coil alone, excited by sinusoidal currents (figure 3), the rates of variation of flux density at the various points are definitely nonsinusoidal. The nonlinear response of the iron to magnetizing force introduces harmonics of considerable magnitude. The influence of core distribution is evident.

With normal excitation for both potential and current elements, the resultant flux variation is not a superposition of those produced by each element acting independently. Portions of the magnetic circuit are influenced by both windings and having a nonlinear response, as stated before, will have resultant magnetic conditions which are not proportional to the component magnetizing forces. The conditions at the various points used to illustrate this are shown for two power factors in figures 4 and 5. In these cases the time relationship between the variations in flux density at the different points is not indicated in these figures.

Because of the difference in timing of the magnetomotive forces of the potential and current elements and the distribution of magnetic core material, the distribution of the resulting flux is not fixed. The variation includes both magnitude and position. Because of this shifting position and magnitude, a variable torque, tending to drive the disk, is produced. This variable torque can be considered as the resultant of many component torques, some positive, some negative. These components can be considered as produced by the fundamentals and harmonics in the space distribution and time variation of the air-gap flux as in any motor.

Although the net instantaneous torque in the case of sinusoidal potential and current is not uniform the single-phase watt-hour meter can be adjusted to give satisfactory registration characteristics. With external circuit conditions such that nonsinusoidal voltage or current or both exist, the proportions of the component

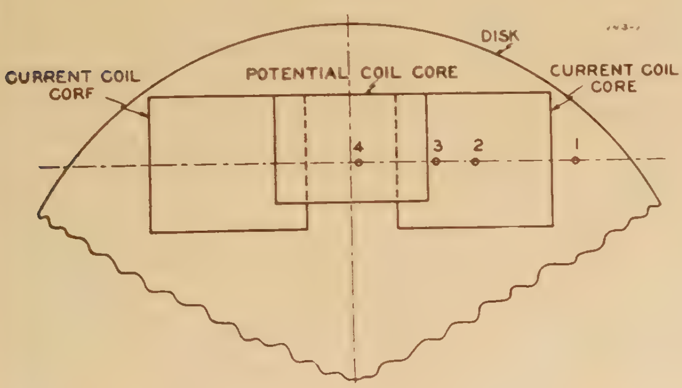


Figure 1. Plan—magnetic core of meter showing survey points

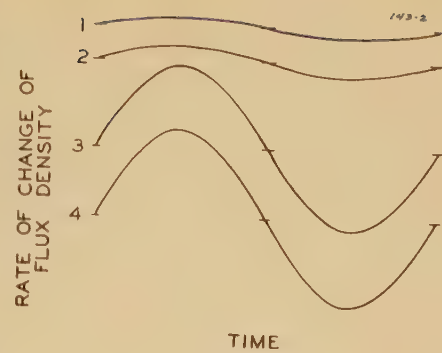


Figure 2. Cyclic rate of change of flux density for rated sinusoidal potential excitation only

Numbers on curves identify the survey points of figure 1

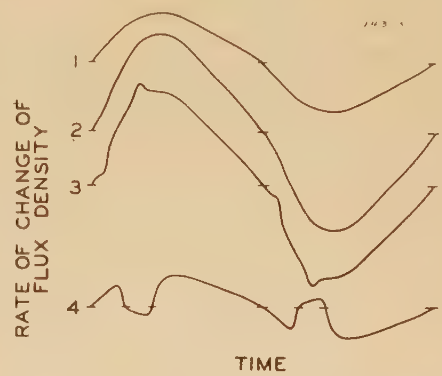


Figure 3. Cyclic rate of change of flux density for rated sinusoidal current excitation only

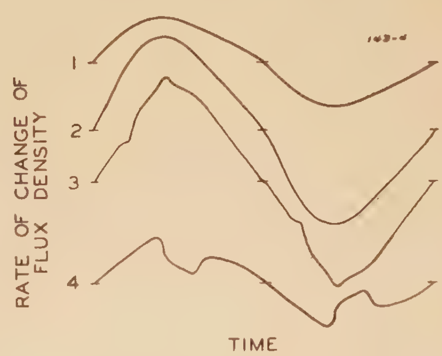


Figure 4. Cyclic rate of change of flux density for both rated sinusoidal potential and rated current excitation at unity power factor

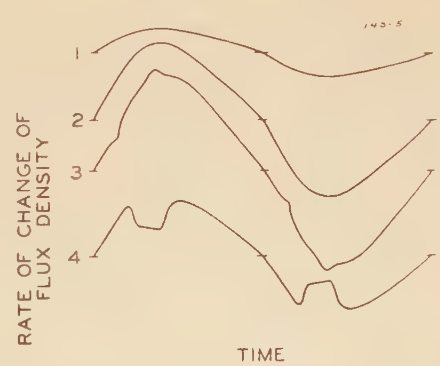


Figure 5. Cyclic rate of change of flux density for both rated sinusoidal potential and rated current excitation at 80 per cent power-factor lag

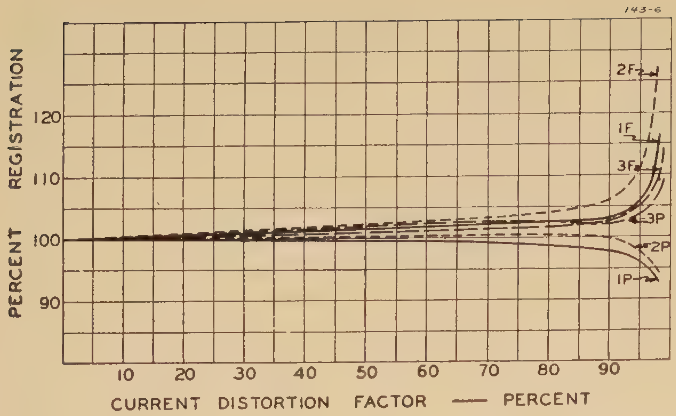


Figure 6. Per cent registration as a function of current-distortion factor for a resistance load with rated sinusoidal potential and rated current (effective value)

Numbers on curves identify manufacturer of meters

Curves *F*—Flat-topped current waves

Curves *P*—Peaked current waves

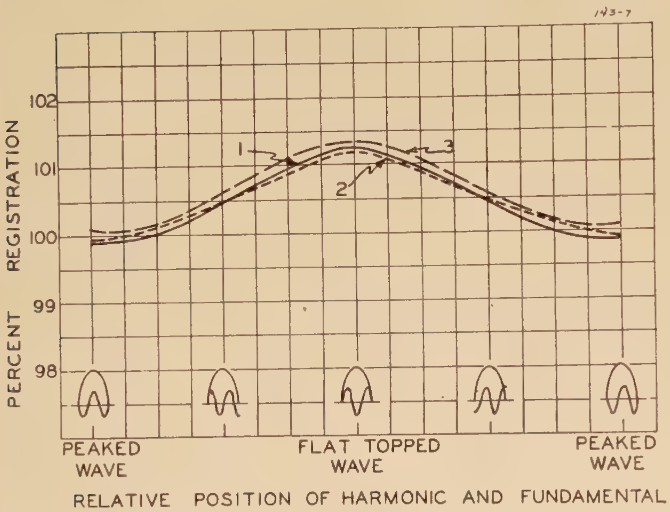


Figure 7. Per cent registration as a function of relative time position of fundamental and harmonic

Sinusoidal potential, constant power, current-distortion factor of 40 per cent

Numbers on curves identify manufacturer of meters

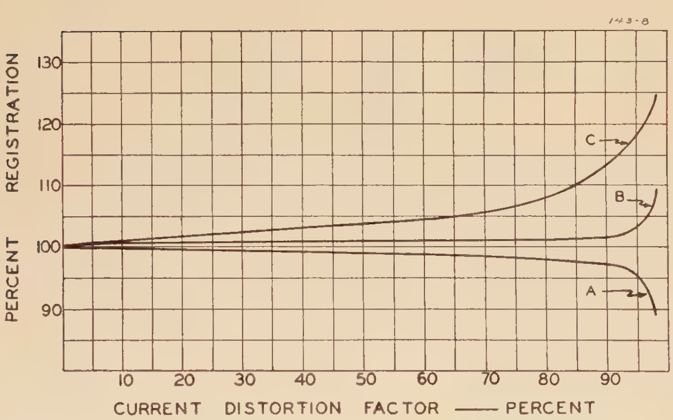


Figure 8. Per cent registration as a function of current-distortion factor for sinusoidal potential and peaked current waves

Curves for meter number 1 at rated current

Curve *A*—Fundamental current in phase with fundamental voltage

Curve *B*—Fundamental current lags fundamental voltage by 37 degrees

Curve *C*—Fundamental current lags fundamental voltage by 60 degrees

torques caused by harmonics will differ from that for which the meter is adjusted and the registration characteristics of the meter altered. The curves of figure 6 show the effects of nonsinusoidal waves of current.

In practical cases, either the voltage or current or both may be essentially sinusoidal functions of time, or either or both may differ sufficiently from the sinusoidal to warrant study. The probable combinations of conditions which may be encountered in practice are (1) both sinusoidal, (2) potential sinusoidal with current nonsinusoidal, (3) both nonsinusoidal. Since the effects of nonsinusoidal conditions are under consideration the base for comparison is taken as the combination (1) namely, the current and potential both sinusoidal.

For cases of nonsinusoidal conditions, varying degrees of distortion as well as various time relationships between harmonic components and the fundamental are considered. For purposes of establishing a measurable effect the distortion was limited to that caused by the presence of a third harmonic. Similar effects should be noted for other harmonics. It will be realized that as the number of harmonic components increases, the number of possible time relationships between the components increases beyond possible experimental study.

The term "distortion factor" is defined as "the ratio of the effective value of the residue after the elimination of the fundamental to the effective value of the original wave." (A.S.A. C-42-1932 section 10.95.430.)

For the case of nonsinusoidal variation of both potential and current an unlimited number of combinations are possible depending upon circuit conditions. Several examples are given, the conditions being noted with the curves showing experimental results.

Experimental Results

The curves of figure 6 show meter registration as a function of the distortion factor of the current wave for three makes of meters of recent design. The potential variation for all cases was sinusoidal. Curves are given for both peaked and flat-topped wave forms. It is evident that the disk speed should decrease as the per cent current distortion increases because under such conditions, the average power decreases. However, for all cases, the meter registration was computed as the ratio of actual disk speed to the disk speed for sinusoidal potential and current conditions giving the same average power. Although the large registration error, indicated on the curves, exists at large per cent values of current distortion, loads of this character are seldom experienced in practice.

For large values of distortion factor, the registrations of the meters with peaked currents differ greatly from those for flat-topped currents. These two wave forms can be considered as limiting cases of the time relationship between the fundamental and third harmonic components of current. For intermediate relationships of the components, intermediate values of the effects would be expected. Figure 7 shows the influence of the time relationship of the components for a constant-load and a constant-current distortion factor of 40 per cent.

Curves are shown for the three makes of meters as in figure 6. It can be noted that for all meters, flat-topped current waves gave the greatest meter registra-

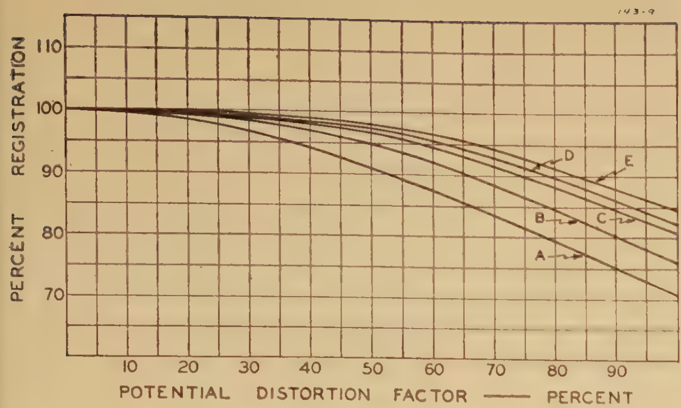


Figure 9. Per cent registration as a function of potential distortion factor for nonsinusoidal potential and current waves

Curves for meter number 1 at several resistance loads for peaked wave form

Curve *A*—20 per cent load
Curve *B*—50 per cent load
Curve *C*—100 per cent load
Curve *D*—200 per cent load
Curve *E*—300 per cent load

tion with a sine wave of potential and that all meters showed about the same performance.

The performance of the meters differed widely for large values of current distortion factor, although all meters were adjusted to give correct registration with zero-distortion factor. Harmonic components in the currents in the current-element windings, through magnetic coupling between those windings and circuits in the details of design, give rise to harmonic currents in those circuits not in exact phase opposition to those in the current coils. These harmonic components may produce torques which have an appreciable magnitude relative to the fundamental torque. It was noted during the tests that 100 per cent current-distortion factor with the potential element unexcited some meters crept backward rapidly, some forward rapidly, and some did not creep. With the potential coil short-circuited or excited, disk movement was reduced in magnitude. At large values of distortion factor the summation of the torques due to harmonics became an important factor in the total torque.

All test meters responded similarly to variations in the phase angle between the fundamental components of potential and current. Figure 8 shows meter registration as a function of distortion factor for peaked waves of current and for three values of fundamental phase angle. The voltage and current were rated values.

For conditions of distortion in both potential and current waves, an unlimited number of combinations are possible. If the load is noninductive the distortion of both the waves should be the same. Under these conditions the time variations of the magnetomotive forces caused by both the potential and current circuits of the meter contain corresponding harmonic components. It should be noted, however, that the presence of corresponding harmonic components in the magnetomotive forces does not imply the presence of harmonic components in the fluxes having the same relative relationships as those of the magnetomotive forces.

Because of the higher frequency, the potential flux per volt for a harmonic is less than that for a fundamental. The variations in the air-gap flux will then be the resultant of components of different relative magnitudes than the respective component voltages. The effects of such conditions on the registration of a typical meter at various per cent loads and for peaked waves are shown in figure 9. Experimental results, using flat-topped waves, differed but slightly from those for peaked waves. In no case was this difference more than one-half per cent. With resistance loading, a reversal or change of any component in the voltage was accompanied by a corresponding change in the current component of that frequency. The net result of the change on the registration of the meters was of no practical magnitude. The flux density at which modern meter cores operate is low enough to make the effects of changing the maximum flux density (caused by change in wave form) small.

When the load circuit is inductive, the distortion factors of potential and current differ. One example of such loading gave results shown in figure 10. In this case, load resistance and inductance were of such values as to produce a fundamental phase displacement of approximately 37 degrees (0.8 power factor) the fundamental current lagging the voltage. Peaked waves of potential were used. The load power was constant.

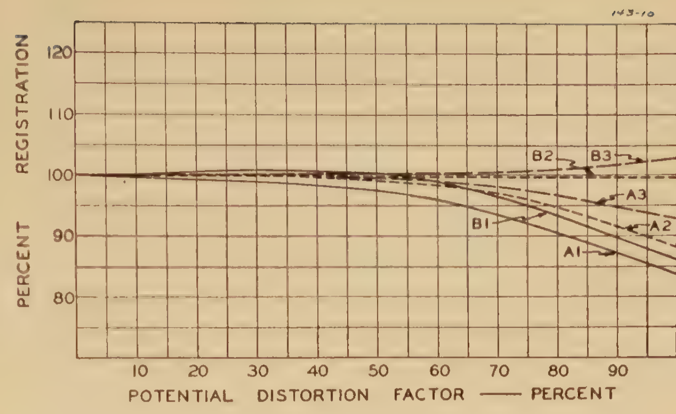


Figure 10. Per cent registration as a function of potential distortion factor for nonsinusoidal potential and current waves

Peaked wave form, two inductive loads
Fundamental current lags fundamental voltage by 37 degrees
Numbers on curves identify manufacturer of meters

Curves *A*— 25 per cent load
Curves *B*—150 per cent load

Conclusions

1. Meter registration errors, as the result of wave distortion, for properly adjusted meters, usually will not exceed the limits of permissible calibration error unless the current-distortion factor is greater than 30 per cent.

2. Indicating instruments are recommended for use in the testing of watt-hour meters when the distortion factor of the current exceeds 50 per cent.

3. No definite statement can be made regarding the effects of distortion on meter registration if the potential distortion is the result of impedance drops caused by distorted currents since the time relationships of the harmonic components depend on circuit conditions.

4. Because of the differences in the space and time variations of the fluxes which would be produced by fundamental and harmonic components of potential, current or both, the net registration of a meter is not the summation of the registrations that the several harmonic components of potential and current would produce, each acting alone.

5. As a result of observations made during the tests it is believed that minor differences in the adjustments required to give satisfactory registration by meters of the same model may cause noticeable differences in the effect of wave distortion on the characteristics of the meters.

6. In the majority of meter applications where minor distortion of current or potential exists the watt-hour meter of recent design measures the energy satisfactorily if adjusted within the limits of commercial accuracy under customary testing conditions.

A New Principle of Cable Design

WM. A. DEL MAR
FELLOW AIEE

Synopsis: Study of cable behavior on load-cycle tests led to the conclusion that instability of the insulation results from its deformation, leaving ionizable voids in the inner layers, where deterioration starts.

This led to the conception of a cable in which the inner and outer layers of paper would have different moduli of elasticity, the outer papers having the higher modulus so that during the cooling period of a load cycle, the outer papers would compress the inner ones and so reduce or eliminate voids therein.

The tension of application of the tapes is the same for all layers and does not depart from ordinary practice.

It was found that cables made on this principle maintained a remarkable stability of power factor under load-cycle conditions.

Finally, a study of cable impregnants showed that an essential characteristic is stability under electrical discharges. An impregnant was developed consisting of a paraffin base oil with a definite proportion of a new synthetic derivative of wood rosin, which possesses this characteristic in a marked degree. This, used in combination with the above-described structure gives the maximum stability we have been able to attain.

IT HAS been the general belief that oil-filled paper cables differ from solid-type paper cables in that the former have a perfect radial and longitudinal flow and ebb of oil throughout the insulation during heat cycles whereas in the latter, the oil flows but does not ebb, perfectly, leaving ionizable voids in the depth of the insulation.

It is undoubtedly true that, in the oil-filled cable, the oil flow is reversible but our researches show that in the solid-type cable, there is little flow of oil out of the insulation at ordinary operating temperatures and, therefore, substantially no trouble to be expected from its imperfect ebb. The view is expressed herein that the real difference between an oil-filled cable and one of solid type is that, in the former, the oil is of such low viscosity that it can flow out and back again under pressure too small to deform the paper permanently, whereas in solid-type cables, the oil viscosity is so great that very high pressures are created by the expanding oil which tend to stretch the paper permanently, creating gaps between tapes which become vacuous when the oil contracts.

This is a useful conception of cable operation and a design of cable based upon it is described, the principle of which is to improve the effective elasticity of the mass of paper by using successive layers of increasing modulus of elasticity, so that each layer will be held in compression by circumjacent layers of greater modulus.

By this means the insulation of solid-type cable acquires some measure of the reversibility characteristic of oil-filled and pressure cables but without adding in any way to the dimensions or complications of the cable or its accessories.

The construction now used consists merely in the use of two layers of paper, the inner comprising three-fourths of the thickness, and the outer, one-fourth of the thickness of the insulation, the paper of the outer layer having a modulus of elasticity 15 per cent to 20 per cent greater than that of the inner layers.

Relative Imperviousness of Impregnated Paper to Viscous Oil Flow

Tests were made to establish the critical viscosity at which oil can move through insulation without exerting enough pressure to put undue stress on the paper.

Typical test results are shown in figure 1. It will be noted that with viscosities above 1,000 to 2,000 seconds there is but little pressure transmission through the insulation. Furthermore, in an operating cable, the oil temperature in the middle of the insulation will be considerably less than at the conductor, so that compound does not flow until the oil at the conductor surface has attained a considerably higher temperature than would be suggested by the data on figure 1.

Elastic Properties of Cable Paper

A study of the elastic properties of impregnated-paper cable was undertaken in order to better appreciate the stresses and strains arising from cyclical loading of cables. A cabinet was constructed capable of holding in vertical suspension a strip of paper one meter in length, changes in length being measured by means of a steel scale graduated in hundredths of an inch. Glued to the end of the paper was a piece of transparent celluloid which extended over the scale and upon which was scratched a hairline. The reading of the hairline was made to one-fourth of a hundredth-inch division through a glass door by means of an instrument-reading telescope. Humidity was regulated by means of anhydrous acids in a dish at the bottom of the tower. Tension was produced by means of a Chatillon spring scale. Humidity was measured by means of a calibrated Taylor humidiguide. The appearance of the setup is shown by figure 2.

It was found that impregnated-cable paper has peculiar physical properties, which would be likely to influence its behavior in a cable. The stress-strain characteristic of a typical cable paper is shown by figure 3. Different papers, however, have different slopes of curve, corresponding to different moduli. Although the graph is a straight line up to about 5,000 pounds per square inch, the paper is not perfectly elastic, within that range, but has a permanent set after each cycle of stretching, the amount of set rising with the tension. The relation between elongation and permanent set was found to be of the form shown by figure 4.

Armed with these data, the next step was to calculate the paper tensions that would result from oil expansion. This was started with the generally accepted idea that this expansion would cause the tape to stretch, thereby separating the layer sufficiently to permit the expanding oil to flow freely outward toward the sheath. The accepted idea was that in cooling, the elasticity of the paper would cause it to close in upon the contracting oil, even to the extent of the outer layers cutting off some of the oil before it could return to the interior of the cable.

It was found, on the contrary, that the paper did not stretch sufficiently to create the necessary oil passages between layers, but that, with the calculated stresses, the permanent set was sufficient to leave voids in cooling.

The obvious step to be taken to improve the quality of cable was to use a truly elastic paper, but we could not find a paper which showed true elasticity when impregnated. All papers tested showed more or less permanent set.

It was noted, however, that different papers had different moduli of elasticity and the idea presented itself of placing layers of paper of high modulus over layers of low modulus so that as the inner papers were stretched by the expanding

Paper 41-71, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 16, 1940; made available for preprinting December 16, 1940.

WM. A. DEL MAR is chief engineer for the Habirshaw Cable and Wire Division of the Phelps Dodge Copper Products Corporation, Yonkers, N. Y.

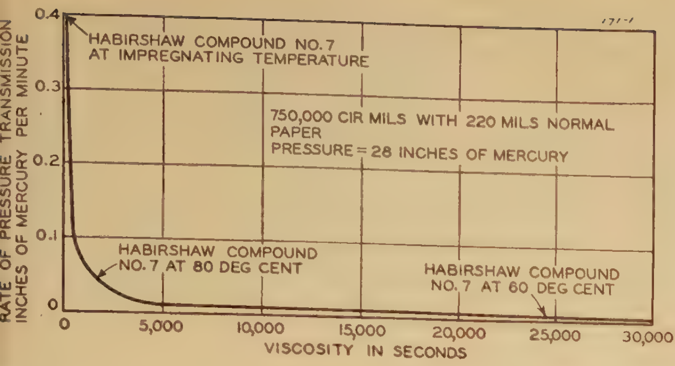


Figure 1. Relative imperviousness of impregnated-paper cable to viscous oil under pressure

Viscosities above 3,500 seconds which could not be measured on the Saybolt universal viscosimeter were measured by rate of penetration through single sheets calibrating the sheets with an oil of known viscosity

Figure 2. Test chamber for modulus determination

oil, they would meet resistance by the outer layers and in cooling, the pressure exerted by these outer layers would help to restore the inner layers to their original condition.

In order to test the correctness of this theory, cables were made with two grades of paper, the inner layers being made with the normal paper and the outer layers with paper having about 20 per cent greater modulus of elasticity. These cables were tested in comparison with cables of normal construction by means of load-cycle life tests.

Accelerated Aging Tests

The best available data on the correlation of accelerated aging with natural aging were those of the Commonwealth Edison Company published by D. W. Roper, AIEE Transactions, volume 52, 1933, page 1028 and by Halperin and Betzer, AIEE Transactions, volume 55, 1936, page 1074.

In order to ensure that our tests should be equally correlated with service conditions we decided to make our tests at the same maximum stress, as in the Halperin-Betzer tests, namely 208 volts per mil and at a conductor temperature five degrees centigrade over the normal operating temperature. When meter corrections were taken into account, our actual maximum stress was 203 volts per mil. The cable type selected for test was a 4/0 AWG, 19 strand, single-conductor cable with 220 mils of insulation and 63 mils lead sheath.

Heating current was maintained for eight hours per day, five days per week. Voltage was maintained the full 24 hours and over weekends, except for intervals while measurements were being made.

Roper reported that tests made under these conditions gave failure of similar nature to those occurring in service and that it would be unnecessary to carry the tests to failure as the rising power factor, ionization and hot-spot temperature would differentiate between cables of different qualities in the course of from two to seven weeks, i.e., 10 to 35 load cycles.

Our preliminary work showed that this generalization was also applicable to our tests.

Poorly impregnated cables, i.e., cables drained of part of their oil, were eliminated in two weeks, i.e., 10 or 12 load cycles.

Questionable cables were eliminated in four weeks, i.e., 20 load cycles.

Good cables, as then made, lasted at least five or six weeks, i.e., 25 to 30 load cycles.

Roper found that whereas tests made at $2^1/_2$ times operating voltage, corresponding to a maximum stress of 208 volts per mil were indicative of service life, those made at three times operating voltage, corresponding to a maximum stress of 250 volts per mil, had no such significance but, on the contrary, were quite erratic.

The suggestion that tests be discontinued before failure, was a fruitful one as it not only enabled more tests to be made in a given time, but also permitted examination of the cable where failure seemed imminent and before destruction of the evidence occurred. The tapes from a typical arrested failure on a cable of ordinary type is shown in figure 5.

As the tests were to be discontinued when the cables showed signs of instability, it was necessary to establish arbitrary limits indicative of this condition.

The Commonwealth Edison limits and those we adopted were as follows:

	Commonwealth Edison Company	Habirshaw
Power factor at 85 degrees centigrade		2.00
Rise of power factor at high temperature of cycle (per cent)	0.75	
Rise of ionization (per cent)	0.50	0.50
Hot-spot temperature rise (degrees centigrade)	8	8

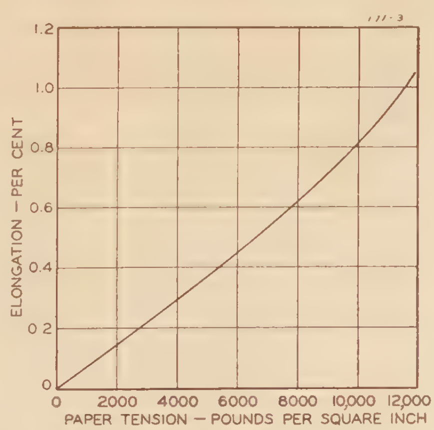


Figure 3. Elongation of normal cable paper impregnated

Each test was made on a set of four cables impregnated at the same time, each 15 feet long and equipped with pressure-tight terminals. The initial power factors on these four supposedly identical cables were nearly equal but not identical. As, however, they tended to equalize after a few load cycles, it seemed fairer to set the limit at a certain final power factor rather than a definite rise from the start. A value of two per cent was chosen as giving results close to those of the Commonwealth Edison Company.

The first load-cycle tests were made with two sets of cables, one made up with 160 mils of normal or type N paper surrounded by 60 mils of high modulus or type S paper, a construction referred to for convenience as "Titebilt," the other

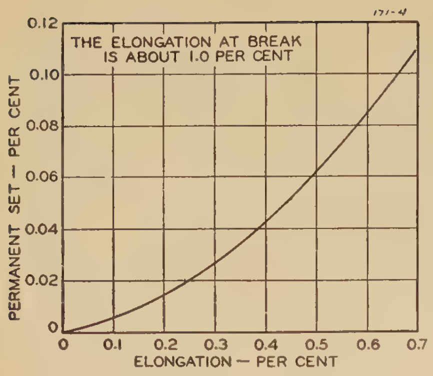


Figure 4. Permanent set of normal cable paper impregnated

made with the same total thickness of paper as ordinarily used, i.e., 50 mils of paper, selected for high density, covered with 170 mils of type *N* paper. The average number of cycles required to reach the limits set were as follows:

Set Number 1

Construction	Power Factor	Ioniza-tion	Hot Spot	Break-down
Ordinary	25	25	22	25
Titebilt	60	82	64	82

Another series of tests was made, adding, however, a set of cables made entirely of type *S* paper. It was expected that if the elasticity theory were correct, the cables made of this kind of paper should be inferior to the Titebilt cable. This was confirmed by the following results:

Construction	Average Number of Load Cycles to Reach Power-Factor Limit Set Number 2
Ordinary construction	30
220 mils of type *S* paper	42
Titebilt	69

The progress of power-factor rise in the Titebilt and ordinary cables for set number 2 is shown in figure 6. It will be noted, that the Titebilt cable shows a smoothly rising curve which contrasts remarkably with the erratic curve of the ordinary cable. The power-factor curve of the Titebilt cable did not show any final upturn until two or three cycles before failure.

The above tests were confirmed by two more sets of tests as follows:

Construction	Load Cycles to Reach Power-Factor Limit Set Number 3	Load Cycles to Reach Power-Factor Limit Set Number 4
Ordinary	27	29
Titebilt	72	75+

Set number 4 was stopped when the Titebilt cable had shown its undoubted superiority.

After all these tests the cables were examined and a large amount of data collected. After the stability of power factor, the first feature noted was the complete absence of dendrites in the Titebilt cables. Cable wax formed in cables of both types, but less frequently and in smaller amounts in the Titebilt type. The exact data are as follows:

Construction	Cables With Dendrites (Per Cent)	Cables With Wax (Per Cent)
Ordinary	36	57
Titebilt	0	25

No gas was found in the tape-edge channels of the Titebilt cables whereas many of the other cables showed varying amounts of gas.

The average ionization of cables of the ordinary type was 0.069 per cent at the end of the life tests whereas that of Titebilt cables was 0.058 per cent in spite of the fact that the latter lasted more than twice as many cycles on life test.

Four lengths of Titebilt cable constituting set number 5 were tested on load cycle at 243 volts per mil, maximum stress which, as indicated above, is too high to yield results comparable with operating conditions. Two of these developed slight dendrites in the *outer* half of the insulation. The dendrites in ordinary cable always appeared in the inner half of the insulation. This shows that the inner part of the insulation, which carries the highest electrical stress at operating voltages, remains tighter in the Titebilt cable, affording an interesting proof of the Titebilt principle. The same peculiarity has since been noted in Titebilt cables tested to breakdown in accordance with AEIC specifications.

In addition to these five recorded sets of tests, there were numerous preliminary tests and tests to obtain specific design data, all of which substantiated the Titebilt design.

Belted Cable

So far, all the discussion has related to single-conductor cable, although obviously, the Titebilt idea is equally ap-

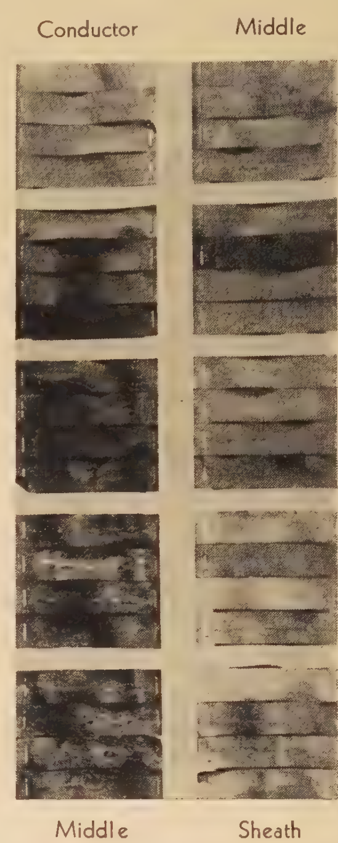


Figure 5. Arrested failure of ordinary cable

plicable to multiple-conductor shielded cable. The principle is not so easily applied to the belted cables, but considerable benefit has been found to result

Figure 6. Life-cycle tests (compound number 7)

Conductor maximum operating temperature = 85 degrees centigrade (approximate)

Sheath maximum operating temperature = 60 degrees centigrade (approximate)

Room temperature = 25 degrees centigrade (approximate)

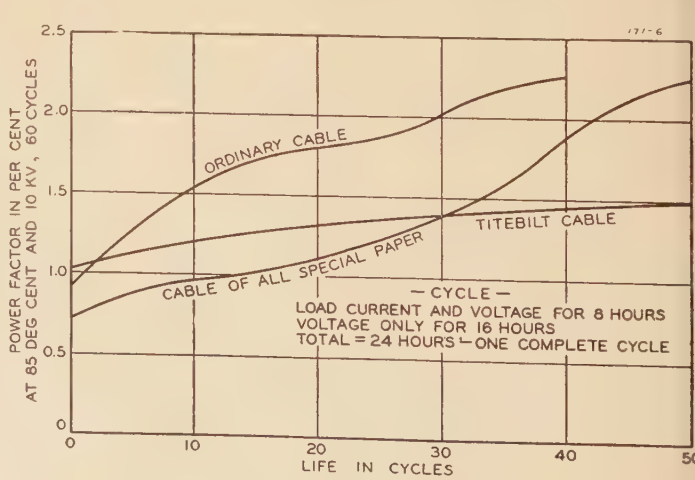


Figure 7. Three-phase load-cycle test equipment

from using the Titebilt composite construction for the conductor insulation.

For instance, one such test was on cable having an AEIC rating of 12,000 volts. It was tested at 24,000 volts; i.e., at twice rated voltage, but the copper temperature was brought up to 85 degrees centigrade. After 30 cycles the Titebilt cable power factor at 85 degrees centigrade rose from 1.01 to 1.06 per cent, whereas that of the old type cable rose from 1.04 to 1.22 per cent. The layout for this test is shown in figure 7.

In general, these tests showed that Titebilt belted cable was consistently superior to the old type cable but by a smaller margin than in the case of the single-conductor and shielded cables.

Compound Number 8

The tests recorded above were all made with compound number 7, a preponderantly paraffin base oil with 15 per cent wood rosin. The following tests were made with cables of the Titebilt construction, using compound number 8 consisting of the same oil with ten per cent of a synthetic derivative of rosin, namely hydrogenated wood rosin.

The type of test on single-conductor cables, described above, proved to be quite inadequate for cables made in this way. It will be remembered that while ordinary cables attained the two per cent power factor (85 degrees centigrade) limit in from 25 to 30 load cycles and the original Titebilt cables in from 60 to 75 load cycles, there was no indication that Titebilt cable with compound number 8 would attain the limit within two or three times that number. In fact, the test seemed to have no effect on the power factor of the cable.

The compound itself, tested, in a new type of bombardment cell, shown in figure 8, gave remarkable results. In preparing a sample of oil for test, the assembled discharge cell is placed on a water bath held at 100 degrees centigrade, and is then evacuated to an absolute mercury pressure of 0.1 millimeter, the residual being air. A sample of oil weighing 25 grams is poured into the funnel of the oil inlet, from which it is slowly drawn into the discharge chamber and degassed. After degassing the apparatus is allowed to stand for one hour at room temperature. At this time, a potential of 9,000 volts, 60 cycles, is applied to the test cell from a gas-sign transformer, and continued for 1,000 minutes. The relative oil stabilities are determined by change of power factor as measured in a Davidson power-factor cell. Whereas in this cell compound number 7 ended the test with a power factor of 4.0 per cent at 85 degrees centigrade, compound number 8 underwent the same ordeal and ended with a power factor of 0.4 per cent. This compound mixes with joint oils, in all proportions, without appreciable rise of power factor.

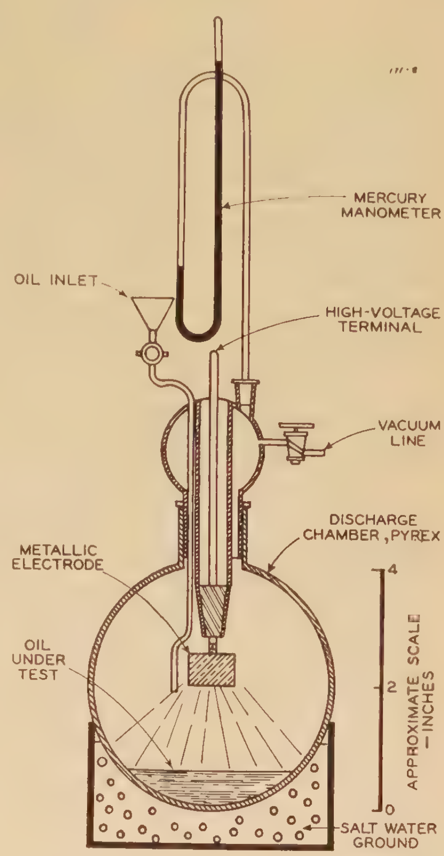


Figure 8. Merrell discharge cell for oil-stability tests

At this stage of our work Mr. Halperin called our attention to a new type of load-cycle test which he had developed that was calculated to be more destructive than the old and we decided to test a three-conductor shielded cable of the new design. This test procedure is described in his 1939 AIEE paper. Like the earlier one, it uses heating and cooling periods with voltage but instead of a single upper temperature of 85 degrees centigrade, it includes cycles at conductor temperatures of 60, 80, 100, and 115 degrees centigrade at twice operating voltage, corresponding to an average stress of 114 volts per mil and a maximum stress estimated at about 195 volts per mil, i.e., substantially the same as in the earlier tests.

The main criteria of stability are the change in the ionization factor at room temperature and in the power factor at 24 kv and 60 degrees centigrade, so that a cycle at that temperature was made after each of the groups of cycles at higher temperatures.

Table I. Load-Cycle Test of Titebilt Cable

Three-Conductor, 500,000-Circular-Mil, Type *H*, 122 Mils of Insulation (Rated at 7,000 Volts), 117 Mils of Lead

Week*	Load Cycles: Number of Cycles	Load Cycles: Maximum Temperature (Degrees Centigrade)	Hours: Heating	Hours: Cooling	Power Factor at 60 Degrees Centigrade (Per Cent)	Ionization Per Cent at Room Temperature
Standard test						
Start					0.39	0.01
1	2	60	7	17	0.39	0.04
	3	80	7	17		
2	1	60	7	17	0.39	0.00
	4	100	7	17		
3	2	60	7	17	0.40	0.01
	3	115	7	17		
4	5	60	7	17	0.39	0.00
Supplemental test						
5	1	60	48	9		
	1	85	15	9		
	2	100	15	9		
	1	115	15	9		
	1	60	15	48	0.40	0.00

*Saturdays and Sundays, after each week of test, the cables carried 24 kv but no load current.

Ionizations which were reported as having small negative values are entered as zero.

Positive and Negative Damping in Synchronous Machines

M. M. LIWSCHITZ
MEMBER AIEE

Synopsis: The straight mathematical analysis of the damping problem on the synchronous machine leads to very complicated results. From these results, the conception of the phenomena occurring in the machine is very difficult and in addition the formulas obtained are so long that the calculation becomes tedious and errors can easily be made. In this paper, an attempt has been made to find a simple physical explanation for the positive and negative damping torques of the synchronous machine and on this basis to derive simpler formulas for the calculation of the damping torques. It has been found that the torque of the synchronous machine, as a double-fed machine, consists of three components, two dependent on the speed of the machine and the third dependent on the angle between the rotating field and the rotor. When the synchronous machine oscillates, the change of the first two components produces positive and negative damping torques of the synchronous machine. The change of the third component produces the synchronizing torque. The positive damping torque depends mainly on the primary voltage and secondary resistance; the negative damping torque depends mainly on the excitation and the primary resistance. This knowledge made it possible to derive a simple and very accurate formula for the positive damping torque as well as a simple approximate formula for negative damping torque. On the basis of these formulas, the influence of the two axes of the machine on the damping can be easily found. A comparison between the results obtained by using the simple formulas and the long accurate formulas as well as a comparison between calculation and test on a small machine have been carried through.

Paper 41-56, recommended by the AIEE committee on electrical machinery, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted October 23, 1940; made available for preprinting December 13, 1940.

M. M. Liwschitz is consulting design engineer for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

1. For all numbered references, see list at end of paper.

I. Simple Equations for Determining the Damping and Synchronizing Torque

For the purpose mentioned, a symmetrical machine will be considered first, both parts of which have polyphase windings carrying currents of different frequencies f_1 and f_2. The frequency f_1 as well as the corresponding voltage E_{L1} are assumed to be constant. All quantities and constants involved will be reduced to terms of this side of the machine. As shown in appendix the torque of such a machine is equal to (all values in per unit notation)

$$T=[e_1^2 s r_2-e_2^2 r_1+e_1 e_2\sqrt{l_1^2+m_1^2}\times \sin(\delta_0+\alpha)]\frac{1}{l^2+m^2} \quad (1)$$

l_1, m_1, l, and m are functions of the slip $s=f_2/f_1$.

Thus the torque consists of three components. The first two components are dependent on the speed of the machine, the third component is dependent on the speed of the machine as well as on the angle between the both line voltages e_1 and e_2. The first component is the well-known torque of the normal induction machine.

The synchronous machine is a special case of the double-fed machine, with $f_2=0$ and $e_2=I_2r_2$.

The three components of the torque T (equation 1) will change their values when the double-fed machine oscillates. To the change of the first two components will correspond a damping torque, to the change of the third component will correspond a synchronizing torque.

Thus the damping torque consists of two components, one positive and the other negative. The positive component is proportional to the square of the primary voltage and is dependent on the secondary resistance; it is equal to zero when the secondary resistance is equal to zero. The negative component is proportional to the square of the secondary

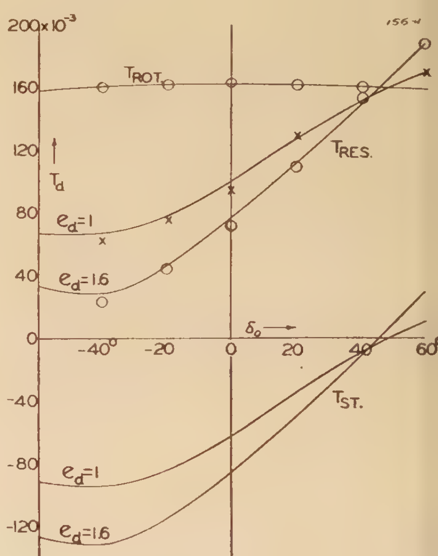


Figure 1. Both axes

A test of this kind on Titebilt cable with compound number 8 is described below.

Shielded Three-Conductor Cable

A cable of the following construction was made, having an AEIC rating of 7,000 volts and tested at 24,000 volts in accordance with procedure described above.

Three-conductor 500,000 circular mils
Insulation 122 mils {type N, 90 mils; type S, 30 mils}
Impregnant, compound number 8
Shield, three-mil copper with intercalated paper
Fillers, paper
Binder, five-mil bronze
Lead, copper bearing, 117 mils
Length of test piece, 25 feet under lead
Position of ends during test, horizontal
Condition during test, pressure tight

The cycles of load are given in table I with the power factors at 60 degrees centigrade at the end of each week. It will be noted that the new Titebilt cable, showed substantially no change in either power factor or ionization. Two cables were subjected to the above test and a third one to the first four weeks only, with the same result. A 115-foot sample of the same cable was subjected, at Chicago, to the same type of test with practically the same results.

Similar tests are recorded by Halperin, AIEE Transactions, volume 58, 1939, page 536, where it is shown that standard 12,000-volt (9/64 inch by 5/64 inch) belted cables made in 1937 and 1938 show power factor increases of 19 to 300 per cent of the original values and ionization rises from substantially zero to 0.5 per cent, absolute values.

While Titebilt cable was developed along the line of scientific utilization of mechanical properties of paper, the disposition of the papers planned on that basis may, and probably does, lead to a better arrangement from other points of view, which I hope to express on some subsequent occasion.

voltage and is dependent on the primary resistance; it is equal to zero, when the primary resistance is equal to zero or when the secondary voltage (in terms of the synchronous machine, the excitation) is equal to zero. The positive component of the damping torque will be called rotor-damping while the negative component will be called stator-damping.

It is now possible to derive a simple formula for the rotor-damping of the synchronous machine (1 and 3). It is (for the symbol s. List of Symbols)

$$T_{\text{rot.}} = \frac{e^2}{Z}\left[\frac{r_{2d}/s_p}{Z_{sd}^2}\sin^2\delta_0 + \frac{r_{Dq}/s_p}{Z_{sq}^2}\cos^2\delta_0\right] \quad (2)$$

where

$$s_p = \frac{Z}{\omega} \qquad \tau_{1d} = \frac{x_1}{x_{ad}} \qquad \tau_{1q} = \frac{x_1}{x_{aq}} \quad (3)$$

$$x_{td} = x_1 + (1+\tau_{1d})x_{2d} \qquad x_{tq} = x_1 + (1+\tau_{1q})x_{Dq} \quad (4)$$

$$Z_{sd}^2 = [(1+\tau_{1d})r_{2d}/s_p]^2 + x_{td}^2$$
$$Z_{sq}^2 = [(1+\tau_{1q})r_{Dq}/s_p]^2 + x_{tq}^2 \quad (5)$$

The rotor damping of the asynchronous machine is determined directly by the slope of the speed-torque curve which is represented by the first component of the equation 1. The rotor damping of the synchronous machine is dependent on this slope at $s=0$ and in addition is modified by the angle δ_0 which determines the power of the synchronous machine.

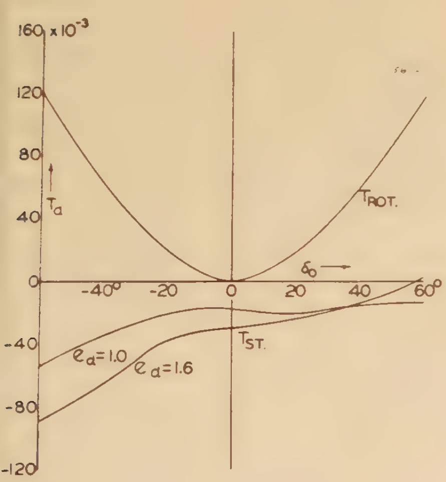


Figure 2. Direct axis

The result given by the equation 2 will be compared with that obtained by Doherty and Nickle in their "Synchronous Machines, Part III"[3] where r_1 is assumed to be equal to zero. The comparison will be made for a 48-pole machine of 2,500 kva, 6,000 volts, 50 cycles, but in order to make the negative damping more noticeable, it will be assumed that this machine has an abnormally high stator resistance, and that it operates on 1,000 volts, 8 cycles per second. Under these conditions, the constants are:

$r_1=0.20$	$r_{2d}=0.022$
$x_1=0.116$	$x_{2d}=0.301$
$x_{ad}=0.855$	$r_{Dq}=0.078$
$x_{aq}=0.519$	$x_{Dq}=0.08$

Further, it is assumed that $Z=5.03$; i.e., $s_p=0.10$.

The curve $T_{\text{rot.}}$ in the upper part of figure 1 was calculated by using the formula contained in said paper, the circles were calculated by using equation 2. The agreement is very satisfactory, as has been found on many other occasions.

Unfortunately, it is not possible to find a similarly simple and accurate formula for the stator (negative) damping. On the basis of the second term of the equation 1 and with support of calculations using the exact formulas it is possible, however, to derive an approximate formula that gives satisfactory results for the usual range of δ_0($\delta_0=+35$ degrees to -35 degrees) and for excitations corresponding to $e_d=1.0$ to 1.6.

When using the second term of the equation 1 it has to be considered that in the synchronous machine the voltage e_2 corresponds to the ohmic drop of the secondary current and that this current multiplied by the reactance of the armature reaction is equal to the electromotive force induced in the stator. Thus the main quantities of the second term of the equation 1 are involved. The influence of the angle δ_0 upon the stator damping is taken into account by two factors k_1 and k_2 based on the exact formulas. Thus, the approximate formula for the stator-damping is:

$$T_{\text{st.}} = -\frac{e_2}{Z}\,\frac{r_1}{\left(\dfrac{x_{ad}+x_{aq}}{2}\right)^2}\times$$
$$\left[\left(\frac{e_d}{e}\right)^2\frac{(r_{2d}/s_p)^2}{Z_{sd}^2}k_1 + \frac{(r_{Dq}/s_p)^2}{Z_{sq}^2}k_2\right] \quad (6)$$

For a generator:

$k_1 = 1 - \tan^2\delta_0 \qquad k_2 = 1 - \sin 2\delta_0$

and for a motor:

$k_1 = 1 + \tan^2\delta_0 \qquad k_2 = 1 - \sin\dfrac{\delta_0}{2}$

The values of the resultant damping torque $T_{d\,\text{res.}} = T_{\text{rot.}} + T_{\text{st.}}$ given by the equations 2 and 6 will be compared with those obtained by Park[4] on the assumption $x_{ad}=x_{fd}$ and $x_{aDq}=x_{aq}$. As in the comparison with Doherty and Nickle, it is further assumed that there is only one winding in the direct axis.

In the figure 1 the curves $T_{\text{res.}}$ are the torques obtained by using Park, the crosses and circles are values calculated

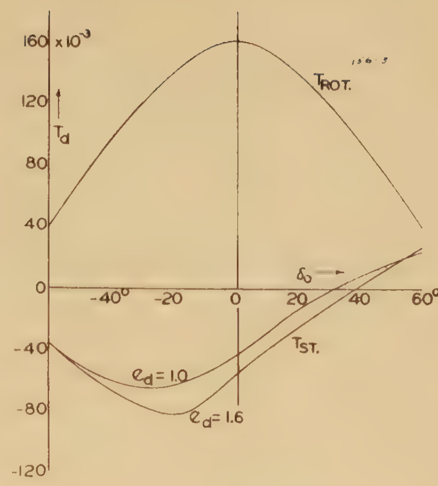


Figure 3. Quadrature axis

from the equations 2 and 6. The agreement is satisfactory. It should be remarked that the damping torques obtained by Nickle and Pierce[5] for the running as a *motor* at the heavier loads are about 30 per cent higher than those obtained by Park; i.e., in this range the method of Nickle and Pierce gives too small values for the negative damping.

In the bottom part of the figure 1 is shown separately the stator (negative) damping torque. The negative damping is much larger when the machine operates as a motor than when it operates as a generator. For the same (absolute) value of the angle δ_0 the resultant damping for the motor is much lower than for the generator. The negative damping torque increases with increasing excitation. This influence of the excitation is also larger for the motor than for the generator The rotor-damping of the synchronous machine is positive for any angle δ_0, while in the normal induction machine the rotor-damping can also be negative. In the normal range of δ_0 the stator-damping of the synchronous machine is always negative, however, at large *positive* values of δ_0 it can become positive.

The figures 2 and 3 show the rotor-damping as well as the stator-damping for both axes separately. For small values of δ_0 the negative-damping in the direct axis is greater than the positive damping, while in the quadrature axis the negative damping is at any angle δ_0 smaller than the positive damping.

The curve T_d of the figure 4 gives the comparison between the results obtained by Park and those obtained by using the equations 2 and 6 for the same machine as above, but at 50 cycles, $s_p=0.027$ and a primary resistance 70 per cent higher than normal. The agreement between both methods of calculation is satisfac-

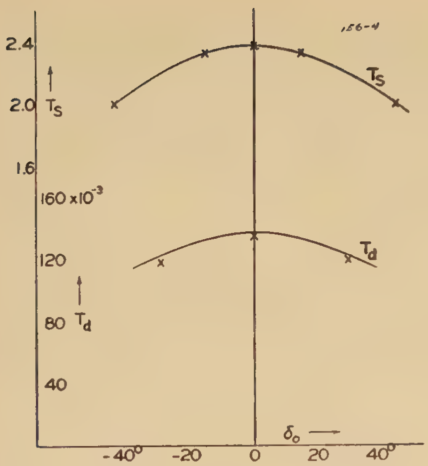


Figure 4

tory. The shape of this curve T_d is typical for the standard larger generators having a low-resistance damper winding. Here the influence of the negative damping is small, and the damping torque can be calculated by using equation 2 only.

The mathematical analysis used in deriving an expression for the damping torque also leads to the synchronizing torque. Since the equations for the synchronizing torque derived in the papers mentioned above (2, 4, and 5) are very complicated, a simple equation for the synchronizing torque was derived that corresponds to equation 2.[11] This equation is

$$T_s=\frac{ee_d}{x_d}\cos\delta_0+e^2\frac{x_d-x_q}{x_dx_q}\cos 2\delta_0+e^2\left[\frac{x_{td}}{(1+\tau_{1d})Z_{sd}^2}\sin^2\delta_0+\frac{x_{tq}}{(1+\tau_{1q})Z_{sq}^2}\cos^2\delta_0\right]\quad(7)$$

The results given by this equation will be compared with those obtained by Doherty and Nickle.[2] The curve T_s in figure 4 shows the comparison for $e_d=1.6$. The agreement is very good, as has been found on other occasions. The correctness of equation 7 is proved by the results of experimental determinations of the natural frequency.

II. Tests to Determine the Damping Torque

There are very few tests published for determining the damping torque of a synchronous machine while the machine is hunting. Some valuable data are given by F. A. Hamilton.[10] Systematic tests, suggested by the author of this paper, were made by R. Kuenmich at the University of Stuttgart.[8] A small 4-pole, 1.6-kva, 50-cycle synchronous machine having an external field system was used in making these tests. The primary resistance was equal to 0.072; the material of the damper winding was copper. The damping torques are given in figure 5*B* for the machine without damper winding and in figure 5*A* for the machine with damper winding. Both diagrams reveal that the damping torque increases with increasing load and that it decreases with increasing excitation. It could not be expected, however, that this influence of the excitation would be appreciable in the large machines used by Hamilton in making his tests.

It follows from figure 5*B* that for the

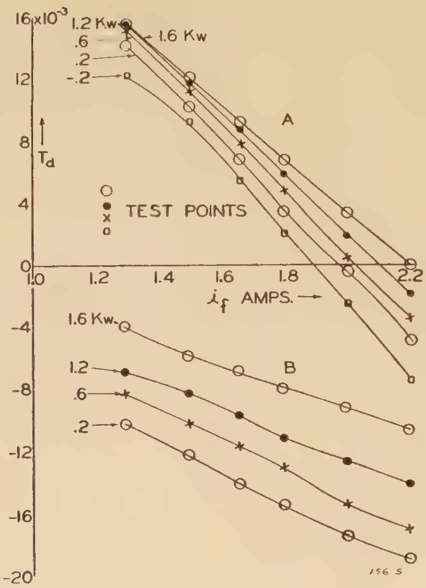


Figure 5

A—Damping torque with damper winding

B—Damping torque without damper winding

point $P=0.2$ kw and $i_f=1.66$ amperes, the torque $T_d=-14.1\times10^{-3}$. By using Park, the calculated torque under these conditions is found to be $T_d=-12.1\times10^{-3}$; by using the equations 2 and 6, it is found to be $T_d=-12.4\times10^{-3}$. The agreement is satisfactory, if it is considered that the accuracy of the tests is from ±10 to ±20 per cent. Figure 5*A* gives for the point $P=1.6$ kw and $i_f=1.66$ amperes, the torque $T_d=9.3\times10^{-3}$. By using Park the calculated torque is found to be $T_d=23.7\times10^{-3}$; by using the equations 2 and 6, it is found to be $T_d=20.6\times10^{-3}$. The calculation does not check with the test. This is only partly a result of the limited accuracy of the tests. The main reason for the discrepancy is the difficulty of properly determining the constants of the machine, especially in the present case, where the saturation is high (the ratio of no-load AT to gap AT being equal 1.57).

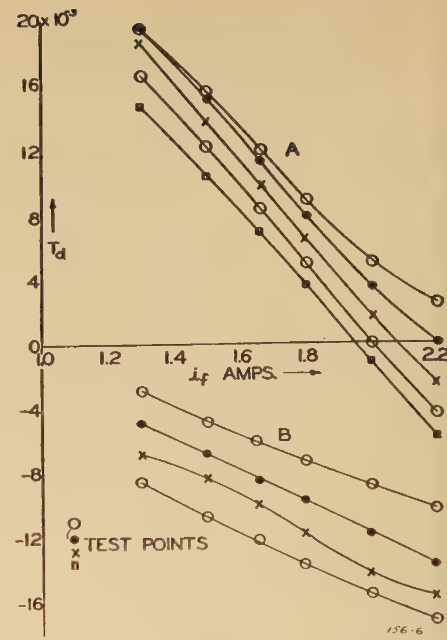


Figure 6

A—One ring open in the middle of the pole

B—One ring open in the middle of the interpolar space

In addition, the frequency of the oscillations is high and therefore the assumptions for the derivation of the formulas are not fully justified. The papers of Linville[7] and Waring and Crary[9] were used in calculating the constants. Only the constants of the damper winding were calculated in another way; namely, in the way shown by the author in a previous paper[12] (i.e., by introducing an equivalent value for the y of Linville).

Figure 6*A* shows the tested damping torques for the same machine, but with reduced influence of the damper winding in the quadrature axis. One of the rings has been cut in the middle of the interpolar space. The damping torque is negative over the entire range, as in figure 5*B* which refers to the machine without damper winding. Figure 6*B* shows the damping torques for the machine with one ring cut in the middle of the pole; i.e., with reduced influence of the damper winding in the direct axis. It is worth noticing that the torques are now larger than in figure 5*A* which refers to the machine with normal squirrel-cage damping. The reason for this can be seen from figure 2. The tested machine has a small angle δ_0 ($\delta_0=11.5°$ at 1.6 kw) and a small angle δ_0 may cause the negative damping in the direct axis to be stronger than the positive damping. In some cases (for example, when the machine is used for electric ship propulsion) it may be useful to cut the ring in the middle of the pole for this would reduce

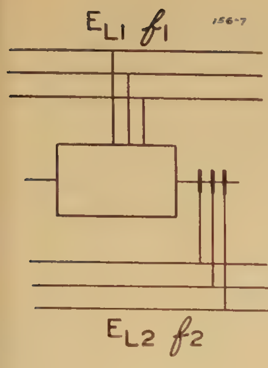


Figure 7

the short-circuit current without appreciably changing the damping torque.

Appendix

For the machine as per figure 7, it will be assumed that the stator voltage E_{L1} and the stator frequency f_1 are constant. All values will be reduced to terms of the stator. If the rotor rotates in the direction of the field produced by the stator currents:

$$n=\frac{120(f_1-f_2)}{p}=\frac{120f_1(1-s)}{p} \qquad s=\frac{f_2}{f_1} \tag{1}$$

Assuming that the iron losses are negligible and that the vectors E_{L1} and E_{L2} are displaced by an angle δ, it is found that

$$\boldsymbol{Z}_1=r_1+jx_1 \qquad \boldsymbol{Z}_2=r_2+jsx_2 \tag{2}$$

$$E_{L1}=-\boldsymbol{E}_1+\boldsymbol{I}_1\boldsymbol{Z}_1 \quad E_{L2}e^{-j\delta}=-s\boldsymbol{E}_1+\boldsymbol{I}_2\boldsymbol{Z}_2 \tag{3}$$

$$\boldsymbol{I}_m=\boldsymbol{I}_1+\boldsymbol{I}_2=j\boldsymbol{E}_1\frac{1}{x_m} \tag{4}$$

The author has shown in a previous paper[13] that it is useful to apply the "superposition principle" in treating the double-fed machine. With this principle, the stator current will consist of two parts, one produced by the stator voltage on the assumption that the rotor is short-circuited, the other produced by the rotor voltage on the assumption that the stator is short-circuited. The same is valid with reference to the rotor current. Thus

$$\boldsymbol{I}_1=\boldsymbol{I}_{11}+\boldsymbol{I}_{12} \qquad \boldsymbol{I}_2=\boldsymbol{I}_{21}+\boldsymbol{I}_{22} \tag{5}$$

From the equations 2 to 5 follow the four current components:

Stator:

$$\boldsymbol{I}_{11}=E_{L1}\frac{f+jk}{l+jm}$$

$$\boldsymbol{I}_{12}=-E_{L2}\frac{\cos\delta-j\sin\delta}{l+jm} \tag{6}$$

Rotor:

$$\boldsymbol{I}_{21}=-E_{L1}\frac{s}{l+jm}$$

$$\boldsymbol{I}_{22}=E_{L2}\frac{(\cos\delta-j\sin\delta)\left(1+\tau_1-j\dfrac{r_1}{x_m}\right)}{l+jm} \tag{7}$$

where

$$\tau_1=\frac{x_1}{x_m},\ \tau_2=\frac{x_2}{x_m},\ f=(1+\tau_2),\quad k=-\frac{r_2}{s}\frac{1}{x_m} \tag{8}$$

$$l=\left[(1+\tau_2)r_1+(1+\tau_1)\frac{r_2}{s}\right]\times s$$

$$m=\left[x_1+(1+\tau_1)x_2-\frac{r_2}{s}\frac{r_1}{x_m}\right]\times s \tag{9}$$

The torque is given by the equation

$$T=E_{L1}\bullet\boldsymbol{I}_1-\boldsymbol{I}_1^2r_1=j\boldsymbol{I}_1\bullet\boldsymbol{I}_2x_m \tag{10}$$

The dot (•) indicates that the scalar product of the two vectors has to be taken. Thus

$$T=j\boldsymbol{I}_{11}\bullet\boldsymbol{I}_{21}x_m+j\boldsymbol{I}_{11}\bullet\boldsymbol{I}_{22}x_m+j\boldsymbol{I}_{12}\bullet\boldsymbol{I}_{21}x_m+j\boldsymbol{I}_{12}\bullet\boldsymbol{I}_{22}x_m \tag{11}$$

By evaluating these four scalar products and using the abbreviations

$$l_1=\left[(1+\tau_2)r_1-(1+\tau_1)\frac{r_2}{s}\right]\times s$$

$$m_1=x_1+(1+\tau_1)x_2+\frac{r_2}{s}\frac{r_1}{x_m} \tag{12}$$

$$\tan\alpha=\frac{l_1}{m_1} \tag{13}$$

the equation 1 will be obtained.

List of Symbols

- e_1, e_2 terminal voltage
- E_L line voltage
- E_I induced electromotive force
- f_1, f_2 line frequency
- f_p frequency of the oscillation
- I current
- I_m magnetizing current
- n revolutions per minute
- p number of poles
- r_1, r_2 resistance
- r_{2d} resultant secondary resistance in the direct axis
- r_{Dq} resistance of the quadrature-axis damper winding
- s slip
- s_p $\frac{Z}{\omega}$
- T torque
- T_d damping torque per radian angular displacement per second
- x_{2d} resultant secondary leakage reactance in the direct axis
- x_{Dq} leakage reactance of the quadrature-axis damper winding
- x_{ad} reactance of armature reaction in the direct axis
- x_{aq} reactance of armature reaction in the quadrature axis
- x_d x_1+x_{ad}
- x_q x_1+x_{aq}
- x_1, x_2 leakage reactance
- x_m reactance due to the main flux
- Z angular frequency of the oscillation
- $\boldsymbol{Z}$ impedance
- δ_0 angular displacement between the axis of the rotor and rotating field corresponding to the average load
- τ leakage coefficient
- ω angular frequency of the line

Bibliography

1. Damping Torque and Design of the Damper Winding of Synchronous Machines, **M. M. Liwschitz.** *Arch. fuer Elektrotechnik*, volume 10, 1921, pages 96–132.

2. Synchronous Machines, Part III, **R. E. Doherty** and **C. A. Nickle.** AIEE Transactions, volume 46, 1927, pages 1–14.

3. Effect of the Damper Winding on the Natural Frequency of the Synchronous Machine, **M. M. Liwschitz.** *Arch. fuer Elektrotechnik*, volume 20, 1928.

4. Two Reaction Theory of Synchronous Machines, **R. H. Park.** AIEE Transactions, volume 48, 1929, pages 716–27.

5. Stability of Synchronous Machines, **C. A. Nickle** and **C. A. Pierce.** AIEE Transactions, volume 49, 1930, pages 338–50.

6. Effect of Armature Resistance on the Hunting of Synchronous Machines, **C. F. Wagner.** AIEE Transactions, volume 49, 1930, pages 1011–24.

7. Starting Performance of Salient-Pole Synchronous Motors, **T. M. Linville.** AIEE Transactions, volume 49, 1930, pages 531–45.

8. Tests to Determine the Effect of a Damper Winding on a Synchronous Machine While Hunting, **R. Kuenmich.** Doctorate Dissertation, University of Stuttgart, 1930.

9. The Operational Impedances of a Synchronous Machine, **M. L. Waring** and **S. B. Crary.** *General Electric Review*, volume 35, 1932.

10. Field Test to Determine the Damping Characteristics of Synchronous Generators, **F. A. Hamilton.** AIEE Transactions, volume 51, 1932, pages 775–9.

11. Synchronizing Torque of the Synchronous Machine, **M. M. Liwschitz.** Scient. Public. of the Siemens Concern, volume 12, 1933.

12. Starting Performance of Salient-Pole Synchronous Machines, **M. M. Liwschitz.** AIEE Transactions, volume 59, 1940, pages 913–19.

13. Application of the Superposition Principle to the Analysis of Control Problems of the Asynchronous Machine, **M. M. Liwschitz.** Scient. Public. of Siemens Concern, volume 8, 1930.

14. The Theory of the Double-Fed Induction Machine, **W. T. Kassianow.** *Electrotechnik und Maschinenbau*, volume 50, 1932, pages 453–7.

Control of the Switching Surge Voltages Produced by the Current-Limiting Power Fuse

E. A. WILLIAMS, JR.
ASSOCIATE AIEE

C. L. SCHUCK
ASSOCIATE AIEE

Synopsis: A new transient condition unique to fuses of the current-limiting type is described and it is recommended that these fuses be designed to inherently control switching surge voltage magnitudes to meet the following conditions:

1. The transient recovery voltage should not exceed the insulation level of rotating machines $\sqrt{2}(2E+1{,}000)$ where E is the rated terminal-to-terminal rms voltage of the lowest rated machine involved.

2. The transient recovery voltage should preferably not exceed the 60-cycle crest spark-over voltage of associated lightning arresters.

3. If the transient recovery voltage does exceed the 60-cycle crest spark-over voltage of associated arresters, the interrupting rating of the fuse should be determined and assigned to limit the arrester current to a safe magnitude.

These conditions may be met by current-limiting fuses employing conducting elements having two or more sections of different diameters. Such fuses have been designed and are now commercially available. Typical oscillograms illustrating the operation of these fuses are included.

Introduction

It is generally recognized that most circuit-interrupting devices may be expected to produce a transient switching surge voltage having a magnitude appreciably in excess of the normal crest voltage. The magnitude of this transient voltage is a function of the characteristics of both the interrupting device and the circuit interrupted. To this background of existing and recognized transient voltage conditions may be added a relatively new phenomenon; the switching surge voltage (transient recovery voltage) of the current-limiting fuse.[1,2] This type of fuse tends to interrupt short-circuit currents so quickly that unless the interruption is properly controlled, the transient recovery voltage may reach a very high magnitude. With proper control, the transient voltage can be held within allowable safe limits.

The switching surge voltage of a current-limiting fuse differs from that of other interrupting devices in that the energy associated with the surge may be considerably greater. This difference results from the fact that the fuse limits the current by rapidly inserting arc resistance into the circuit at the instant the current-responsive element volatilizes. Since the high-resistance steady-state arc voltage of the fuse is practically equal to open-circuit voltage, the "recovery" occurs at the inception of the arc and *before* the interruption of the short-circuit current. With other interrupting devices, the voltage recovers at the end of the arcing period and *after* the interruption of the short-circuit current. Thus, the switching surge voltage of the fuse is associated with a definite value of dynamic short-circuit current and for this reason a new conception of the effects of transient recovery voltage must be considered.

The purpose of this paper is:

1. To call attention to the nature of a new switching transient phenomenon.

2. To point out the desirability of controlling the new switching transient to prevent damage to associated equipment.

3. To describe a method of designing current-limiting fuses with effective means of controlling switching surge voltages.

Permissible Limits for Switching Surge Voltages

Permissible limits for switching surge voltages should be based on several factors, one of which is the insulation level of rotating machines. Transformers and similar apparatus are considered to have an impulse ratio in the order of two or more, whereas rotating machines should be considered to have an impulse ratio only slightly greater than unity.[3] For

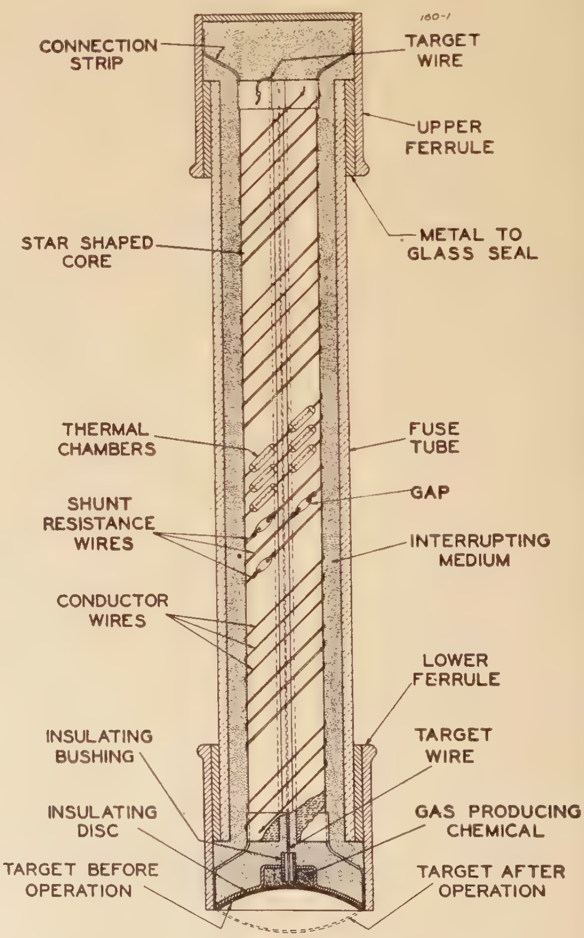


Figure 1. Current-limiting fuse with shunt-resistance wires

Paper 41-60, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 28, 1940; made available for preprinting December 13, 1940.

E. A. Williams, Jr., and C. L. Schuck are in the switchgear engineering department of the General Electric Company, Philadelphia, Pa.

The authors wish to acknowledge the parallel work of several European companies along the lines described in this paper. The contribution of K. A. Lohausen, Allgemeine Elektricitäts-Gesellschaft, is particularly noteworthy.

1. For all numbered references, see list at end of paper.

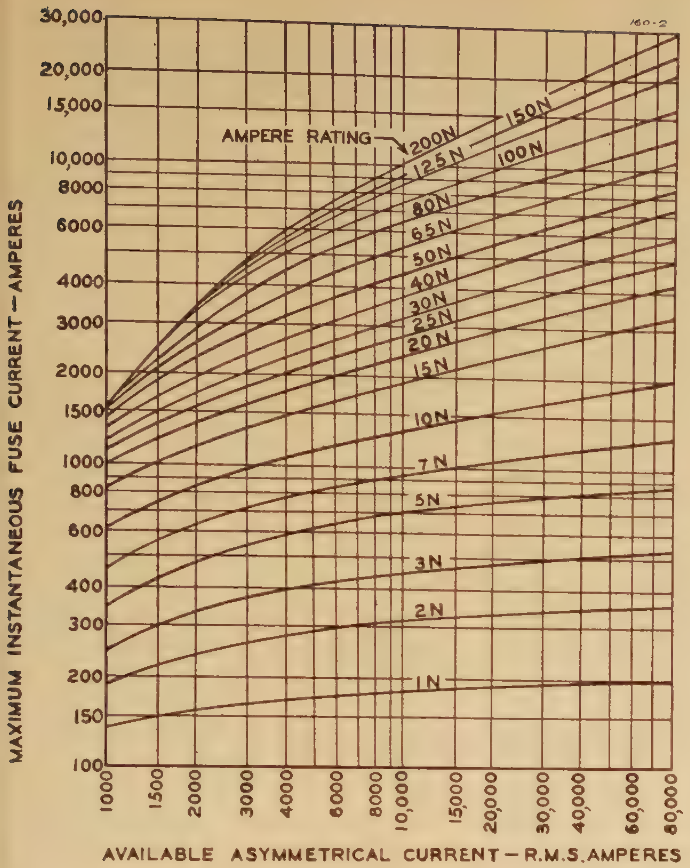


Figure 2. Maximum instantaneous current permitted by a line of current-limiting type fuses

the purpose of selecting permissible limits of switching surge voltage, safe practice will be adhered to by considering the crest value of the machine's one-minute high-potential test voltage as the maximum value of allowable transient voltage. The first logical limitation is then $\sqrt{2}(2E+1{,}000)$ where E is the rated terminal-to-terminal rms voltage of the lowest rated machine connected to the circuit in which the fuse is to be applied. For example, the limit for a 5,000-volt fuse is based on $E=4{,}000$ since this is the lowest rated machine in the 5,000-volt class. Since all other apparatus appears to have a higher insulation level than rotating machines, this limit should be entirely safe from a consideration of insulation alone.

A second and less obvious limit is imposed by the possibility of the operation of lightning arresters during voltage surges which would not damage insulation. The minimum 60-cycle spark-over voltage of an arrester is 1.5 times its maximum permissible line-to-ground voltage (proposed revision AIEE Standard 28) and its average spark-over voltage is somewhat higher. It is obviously desirable to minimize the number of arrester operations in all cases and to eliminate unnecessary operations wherever possible. Therefore, it becomes apparent that a desirable limit for switching surge crest voltages is 1.5 times the maximum crest rating of arresters used on the circuits for which the fuses are designed.

It has been found practical to design current-limiting fuses, as described later, to inherently limit switching surge voltages to magnitudes below the crest of the 60-cycle spark-over voltage of arresters which are rated above the voltage rating of the fuse. However, good engineering practice dictates the application of current-limiting fuses capable of interrupting line-to-line voltage whereas operating experience justifies the use of lower rated arresters on solidly grounded neutral systems. Therefore, since a line-to-line rated fuse may be expected to produce a switching surge voltage somewhat higher than the crest of normal line-to-line voltage, the associated line-to-neutral arrester is subject to spark over during every fuse operation. This condition does not exist when the fuses and arresters are *both* applied on the basis of line-to-line voltage.

When an arrester sparks over while a current-limiting fuse is interrupting a circuit, the two devices divide the dynamic short-circuit current in inverse proportion to their respective resistances. As previously pointed out, this current may be considerably higher than that ordinarily associated with switching surge voltages and its duration may be in the order of 1,000 to 1,600 microseconds. The ability of an arrester to pass current for relatively long periods of time is limited by economic considerations and this limit is recognized in AIEE Standard No. 28. It therefore becomes advisable to determine and assign interrupting ratings to fuses in a way that the short-circuit currents permitted by the fuses, when arresters are subject to spark over, are limited to values such that the arresters may safely pass their share of current without damage to the arresters.

From the considerations discussed above, it may be concluded that fuses of the current-limiting type should be so designed that switching surge voltages are inherently controlled to meet the following conditions:

1. The transient recovery voltage should not exceed the insulation level of rotating machines $\sqrt{2}(2E+1{,}000)$ where E is the rated terminal-to-terminal rms voltage of the lowest rated machine involved.
2. The transient recovery voltage should preferably not exceed the 60-cycle crest spark-over voltage of associated lightning arresters.
3. If the transient recovery voltage does exceed the 60-cycle crest spark-over voltage of associated arresters, the interrupting rating of the fuse should be determined and assigned to limit the arrester current to a safe magnitude.

Designing Current-Limiting Fuses to Control Switching Surge Voltages

One method of controlling transient recovery voltages to meet specified limits has been used for two years in commercially available fuses. It consists essentially, figure 1, of resistance wires, in parallel with the conducting wires, through which the energy of the surge is shunted and absorbed. The currents which the shunt-resistance wires must handle are shown as the ordinates of the curves of figure 2. The practical application of this principle appears to be limited to fuses rated approximately ten amperes and below as the required ability of the shunt-resistance wires to absorb surge energy increases rapidly as the continuous-current ratings of the fuses increase. Since the shunt-resistance wires occupy space and serve no useful purpose during normal current conditions, it is obvious that the fuses may be made smaller and less costly by combining the voltage limiting and current-carrying functions. This desirable result may be obtained by controlling the growth of arc resistance during the interrupting process. The conducting elements, schematically shown in figure 3, form a basis for the reliable control of arc resistance.

The resistance of an arc is a function of its diameter, length, and the magnitude of current in the arc. The voltage which appears across the fuse at any instant during current interruption is the product of the arc resistance and arc current at that instant. Neglecting other circuit resistance which may be present, this condition may be expected by the fundamental equation:

$$e=ri+L\frac{di}{dt} \tag{1}$$

where

e = generated voltage
r = arc resistance
i = arc current
L = circuit inductance
t = time

Therefore, it is apparent that the rate and amount of arc resistance inserted in the circuit determines the rate of rise and magnitude of the transient recovery voltage.

When the available short-circuit current is of such magnitude that the current is appreciably limited by the fuse, it has been found empirically that the arc resistance of the fuse at the instant of surge voltage crest, is directly proportional to the arc length. The arc length at any instant is in turn equal to the length of the conducting element which has been volatilized. The number and diameter of the conducting elements volatilized also influence the arc resistance, at the instant of surge voltage crest, as indicated by the following empirical equation:

$$r=[K_1-(K_2+K_3d^3)\sqrt{n}]l \tag{2}$$

where

r = arc resistance at instant of surge voltage crest
d = diameter of conducting elements
n = number of conducting elements
l = arc length
K_1 K_2 K_3 = constants

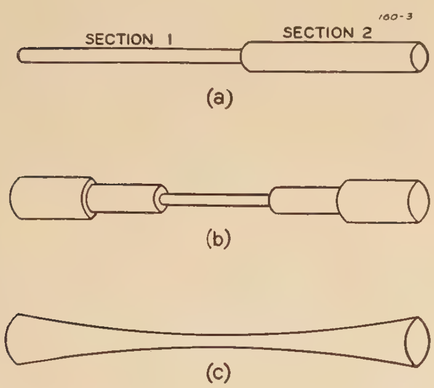


Figure 3. Conducting elements (schematic) showing use of progressive steps in cross section

The surge voltage crest may then be expressed as:

$$V=ir=i[K_1-(K_2+K_3d^3)\sqrt{n}]l \tag{3}$$

Where i is the instantaneous current at surge voltage crest as given by the curves of figure 2.

Since the values of d and n are fixed within narrow limits by the continuous-current rating and the interrupting rating of any given fuse[4] and since the maximum value of i is also determined by the interrupting rating of the given fuse, equation 3 reduces to the simple form:

$$V=Kl \tag{4}$$

The accuracy of equation 4 has been established by hundreds of comparative interrupting tests. This equation provides the basis for a new and effective method of controlling switching surge voltages of current-limiting fuses. To hold the crest voltage to a value V_1, it is only necessary to determine the value of K for the fuse rating concerned and solve equation 4 for the length of the conducting element, l_1, which may be vaporized at the time V_1 occurs. The length of conducting element so determined may be, and in most cases is, less than the minimum length required to safely interrupt the circuit. Therefore, it is necessary to provide additional conducting element length which, when vaporized, will produce sufficient additional arc resistance to effect interruption.

To prevent the crest voltage produced by the added length of element from superimposing itself on the first crest, the vaporization of the added length of element must be delayed until the first surge has declined. The necessary delay may be obtained readily by designing the added element length with a larger cross section than the original length as indicated in figure 3a.

The time required for the first surge to reach its crest and decay is in the order of 100 to 150 microseconds with short-circuit current at or near the interrupting rating of the fuse. This fact has been established by hundreds of short-circuit tests on fuses of various current ratings. Typical cathode-ray oscillograms of the transient voltage conditions during these tests are shown in figure 4. It may therefore be concluded that the diameters of the two sections of conducting element, figure 3a, should be so designed that section 2 is vaporized at least 150 microseconds after section 1.

The factors contributing to the magnitude of the surge produced by section 2 of the conducting element are essentially the same as those which determine the first surge. However, the initial conditions for the second surge differ from those of the first surge in that the short-circuit current has declined to a lower value and the initial voltage is at least equal to the normal frequency voltage at that instant. With these exceptions, the maximum length of section 2 may be determined from equation 4 with the proper evaluation of constants. The optimum element design is that which gives the minimum

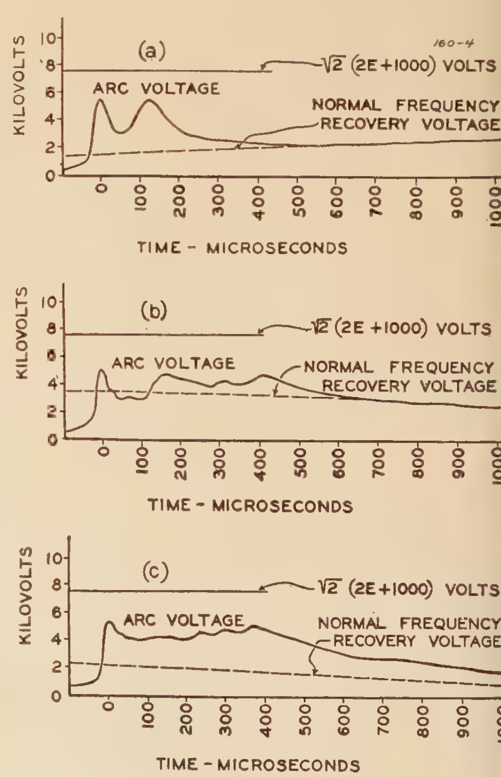


Figure 4. Typical oscillograms of controlled transient recovery voltage produced by current-limiting fuses

(a)—Fuse rating—2,500 volts, 10 amperes
Test voltage—2,500 volts
Available rms current—21,000 amperes
Phase angle of generator voltage at time of first surge crest—24 degrees

(b)—Fuse rating—2,500 volts, 40 amperes
Test voltage—2,500 volts
Available rms current—23,000 amperes
Phase angle of generator voltage at time of first surge crest—90 degrees

(c)—Fuse rating—2,500 volts, 100 amperes
Test voltage—2,500 volts
Available rms current—27,000 amperes
Phase angle of generator voltage at time of first surge crest—145 degrees

A Vertical-Flow Outdoor Compressed-Air Breaker

L. R. LUDWIG
ASSOCIATE AIEE

B. P. BAKER
ASSOCIATE AIEE

1. Introduction

THE elimination of oil in indoor circuit breakers, particularly for powerhouse use, has been insistently demanded to reduce fire hazard. In an effort to meet these requirements, various types of breakers not containing oil have been built and studied. Self-contained breakers of the "De-ion" type[1] have been available for several years, and the potentialities of water breakers[2] have been carefully investigated. Compressed-air breakers[3] for this service have been successfully developed, particularly to meet high kilovolt-ampere interrupting requirements, and the circuit-rupturing ability of these devices has been so amazingly efficient that experimental breakers using this principle have now been built and tested for high-voltage outdoor application.

2. Interruption With Compressed Air

Compressed-air breakers for interrupting medium powers have been in use in Europe for ten years, but these devices have not been available in America until recently. The longitudinal flow-type interrupter, generally used in Europe, was investigated and found to be very satisfactory for moderate values of current, but its inherent limitations made it impractical for the medium and high kilovolt-ampere requirements at powerhouse voltages. On the contrary, an interrupter using a blast of compressed air and insulating splitters disposed perpendicular to the arc, was found to be very effective and not subject to the same arc-current limitations. Structurally, it was also found well adapted for use with high-current carrying contacts.

Just one year ago, the $1^{1}/_{2}$-million kva, 15-kv compressed air circuit breaker[3] of the transverse-flow type was reported, and oscillograms of single-phase operations at 13.2 kv up to 65,300 amperes rms were shown. Since then, the same $1^{1}/_{2}$-million kva breaker has been successfully demonstrated at 13.2 kv, 3 phase up to 86,500 amperes, and this type of interrupter is now being built into a $2^{1}/_{2}$-million kva, 15-kv breaker for 4,000 amperes continuous current-carrying capacity. Currents in excess of 100,000 amperes can be interrupted with this breaker using tank pressures not greater than 150 pounds per square inch.

The theory of this interrupting process in breakers of this type has been studied. The effectiveness of the cross-blast, splitter-type interrupter appears to depend on, first, the fact that a number of interrupting elements or splitters can easily be used in series, and second, the use of a gas-forming material such as fiber for the splitter. The function of the gas-forming splitter elements is largely to introduce turbulence into the arc stream to enhance the deionization by diffusion, following a current zero. Slepian[4] has described this theory in detail.

As breaker voltages are increased from 15 kv or 34 kv, the problem of insulation becomes of increasing significance and it becomes more difficult to design a satisfactory structure which operates on the cross-blast principle. Fortunately, the currents to be interrupted decrease as the voltage increases but not to a sufficient extent so that plain metallic nozzle interrupters can be used with moderate air pressure. Consequently, for the higher voltages it has been necessary to develop a new type of interrupting element which lends itself to vertical porcelain-clad breaker construction and provides high-interrupting ability.

3. Vertical-Flow Compressed-Air Interrupter

The reasons cited for the success of the cross-blast interrupter suggest that a satisfactory form of device can be built for higher voltages by using fiber disks horizontally disposed. These disks have central orifices through which the arc is drawn and through which a vertical flow of air passes to effect the interruption. One or more of such elements can be placed in series, and a dual interrupter of this type is shown in figure 1. It consists of two fiber disks with a metal insert in the center. These inserts have centrally located holes which form the orifices. Between these orifice disks another

Paper 41-54, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 28, 1940; made available for preprinting December 12, 1940.

L. R. Ludwig is division manager and B. P. Baker research engineer for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

1. For all numbered references, see list at end of paper

---

voltage at any instant during interruption. This condition exists, other factors being equal, when both surges reach the same crest magnitude.

The desired limit of switching surge voltage cannot always be met, and successful interruption obtained, by the simple two-section conducting element. In such cases, it is necessary to extend the same design principles to include multisection conducting elements similar to that shown in figure 3*b*. Carried to its logical extreme, this procedure would result in conducting elements characterized by a smooth taper as indicated in figure 3*c*. However, from practical economic and manufacturing considerations, these tapered elements cannot yet be justified.

Conclusion

The control of fuse switching surge voltages by the use of conducting elements with uniform sections of different diameters has proved both practical and flexible. Current-limiting fuses employing this principle have been designed and are now commercially available. Comprehensive tests have shown that these fuses consistently limit the switching surge voltages to magnitudes within the acceptable levels given in the first part of this paper.

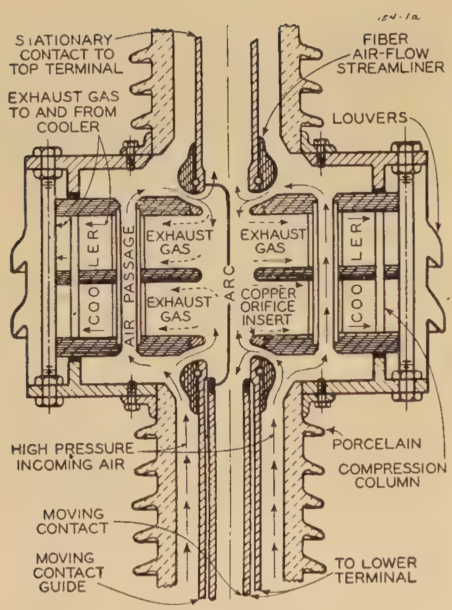
References

1. THE CURRENT LIMITING POWER FUSE, D. C. Prince and E. A. Williams, Jr. AIEE TRANSACTIONS, volume 58, 1939 (January section), page 11.

2. A NEW CURRENT LIMITING FUSE, H. L. Rawlins, A. P. Strom, and H. W. Graybill. AIEE TRANSACTIONS, volume 60, 1941 (February section), pages 77–80.

3. PROTECTION OF ROTATING A-C MACHINES AGAINST TRAVELING WAVE VOLTAGES DUE TO LIGHTNING, W. J. Rudge, Jr., R. W. Wieseman, and W. W. Lewis. AIEE TRANSACTIONS, volume 52, June 1933, page 434.

4. Discussion of the paper, THE CURRENT LIMITING POWER FUSE, D. C. Prince and E. A. Williams, Jr. AIEE TRANSACTIONS, volume 58, 1939 (January section), page 16.



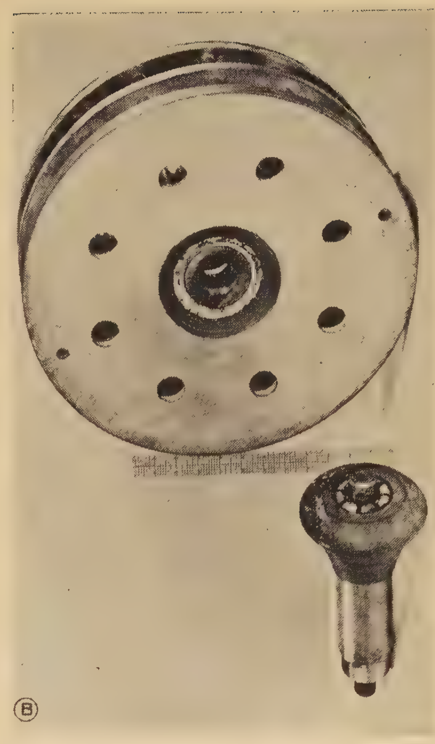


Figure 1. The interrupting element of a 138-kv vertical-flow outdoor compressed-air circuit breaker

(Above) Schematic diagram showing air flow

(Right) Photograph of interrupter and contact after heavy duty tests shown in tables I and II

insulating plate is introduced which restrains the random motion of the arc in the exhaust gas. The interrupter is symmetrical about this insulating plate so that the stationary contact and the upper orifice form one working unit. Likewise, the moving contact and the lower orifice plate form another. The contact members are hollow to permit a portion of the air blast to pass through them. The metal inserts in the fiber disks are used to lessen erosion and enlargement of the hole in the disks.

The air blast passes through the porcelain below the interrupter where part of it escapes through the lower working unit. The remainder passes through the tubes in the interrupter to the upper porcelain from which it escapes through the upper working unit. The air, as shown in figure 1, approaches the arc in a radial direction from between the orifice plate and the streamliner of the contact. Upon reaching the arcing space, it turns and flows vertically along the arc stream, some of it escaping through the contacts while the greater portion escapes through the orifice plate.

It has been found experimentally that this combination is better than a solid conductor and an orifice, or two orifices with equal discharge area. The unsymmetrical flow of air serves to eliminate a "dead spot" in the center which is not readily deionized, and likewise the arc terminal is carried into the hollow of the contact, so that the flow of air carries the metallic vapor from the arc terminal out into the vent instead of into the restricted portion of the arc path where the growth of dielectric is the greatest. The smaller quantity of gas which is discharged through the contacts escapes out the top of the breaker and into the mechanism box. The greater amount which passes through the orifices escapes radially between the orifice plates and is cooled by the screening placed in the annular space formed by the two orifice plates, the air tubes, and the pin supports.

This very simple arrangement gives in reality two interrupting or working combinations in series. The first, consisting of the stationary contact and the upper orifice, which becomes effective with the first third of the contact motion,

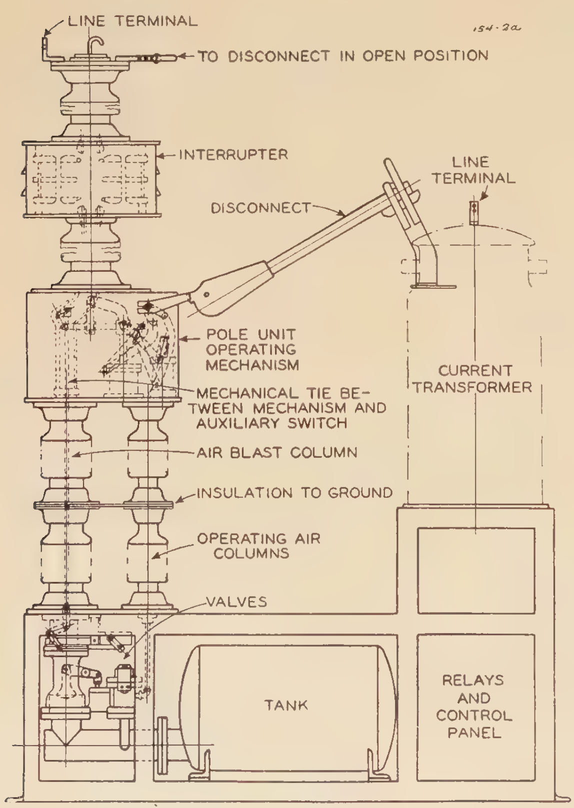


Figure 2. Single-pole 138-kv vertical-flow outdoor compressed-air circuit breaker

(Left) Schematic diagram

(Right) Photograph of breaker mounted in the high power laboratory

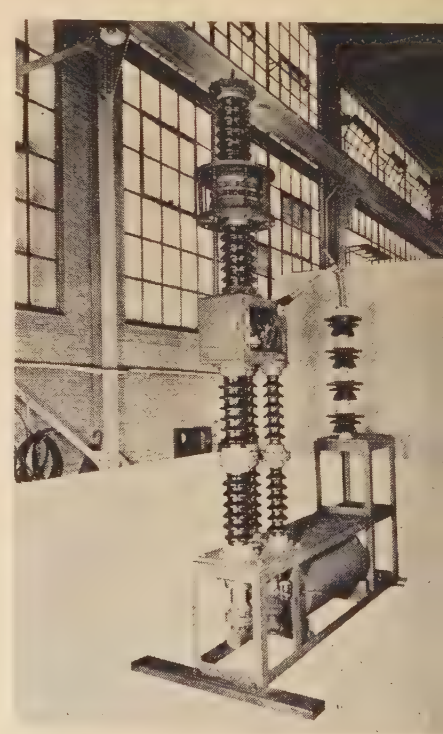


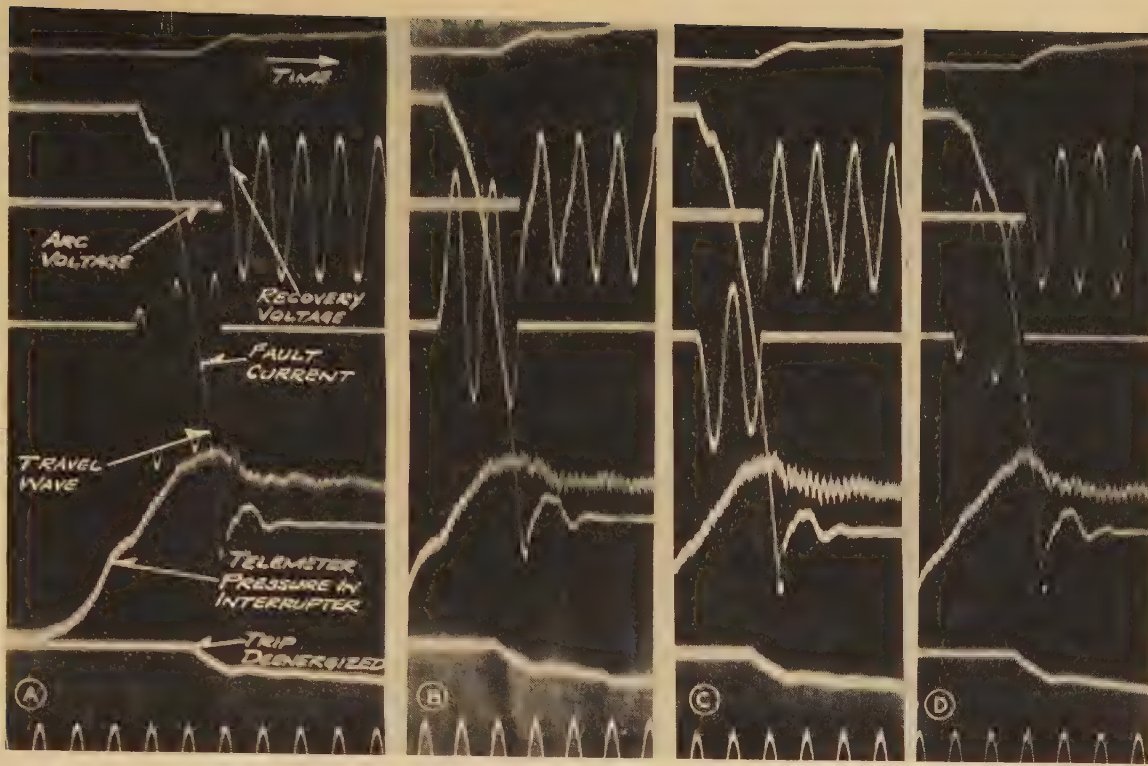
Figure 3. Magnetic oscillograms from table I. Current and voltage values noted are rms values per AIEE Standards

A—Fault current, 5,840 amperes recovery voltage, 123 kv

B—2,520 amperes, 123 kv

C—7,150 amperes, 123 kv

D—8,900 amperes, 123 kv



The second, consisting of the moving contact and the lower orifice, which becomes effective during the last third of the contact motion. In practically every interruption, with currents, voltages, and voltage-recovery rate typical of commercial applications arc extinction is obtained in the first working unit.

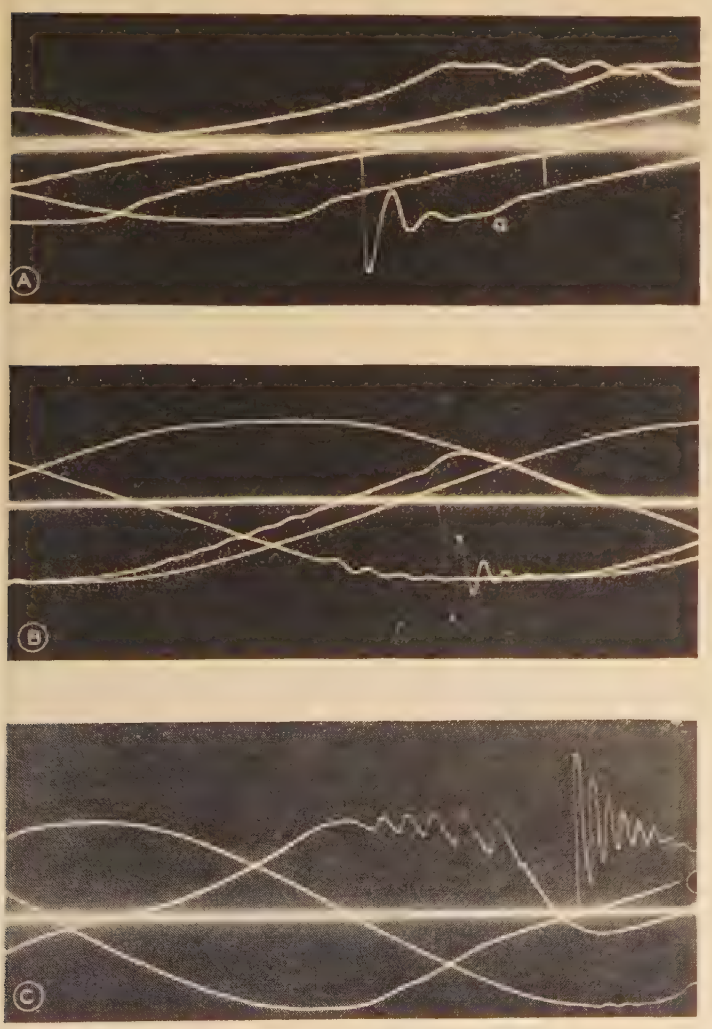


Figure 4. Cathode-ray oscillograms corresponding to those in figure 3

A—Fault current 2,520 amperes rms. Restored voltage 123 kv. Oscillatory frequency 2,600 cycles per second. Recovery rate 1,750 volts per microsecond. Maximum instantaneous voltage 296 kv

B—Fault current 5,840 amperes rms. Restored voltage 122 kv. Oscillatory frequency 3,660 cycles per second. Recovery rate 2,310 volts per microsecond. Maximum instantaneous voltage 264 kv

C—Fault current 8,900 amperes rms. Restored voltage 123 kv. Oscillatory frequency 4,310 cycles per second. Recovery rate 2,970 volts per microsecond. Maximum instantaneous voltage 295 kv

4. 138-Kv Compressed-Air Breaker

Figure 2 shows both a photograph and a schematic diagram of a single-pole unit 138-kv experimental breaker. The usual air storage tank is mounted in a simple frame which also houses the electrical relaying equipment, blast valve, and valves to supply air for opening and closing the breaker. The air-blast valve is mechanically interlocked with the opening valves so that the contacts cannot part without sufficient air for arc extinction. The operating valves are also interlocked pneumatically so that the opening operation always takes preference over the closing operation. The blast valve located adjacent to the tank discharges into a hollow porcelain insulator which carries the air direct to the interrupter chamber with a minimum of length and turns. The operating mechanism is at line potential when the isolating disconnect switch is closed and engaging the current transformer or the top of a post insulator which forms the one line terminal. The other line terminal is at the top of the breaker. The interrupting element is halfway both electrically and mechanically between the top terminal and the operating mechanism. When the breaker is in the open position, the disconnect removes potential from the interrupter and short-circuits it by engaging suitable clips at the

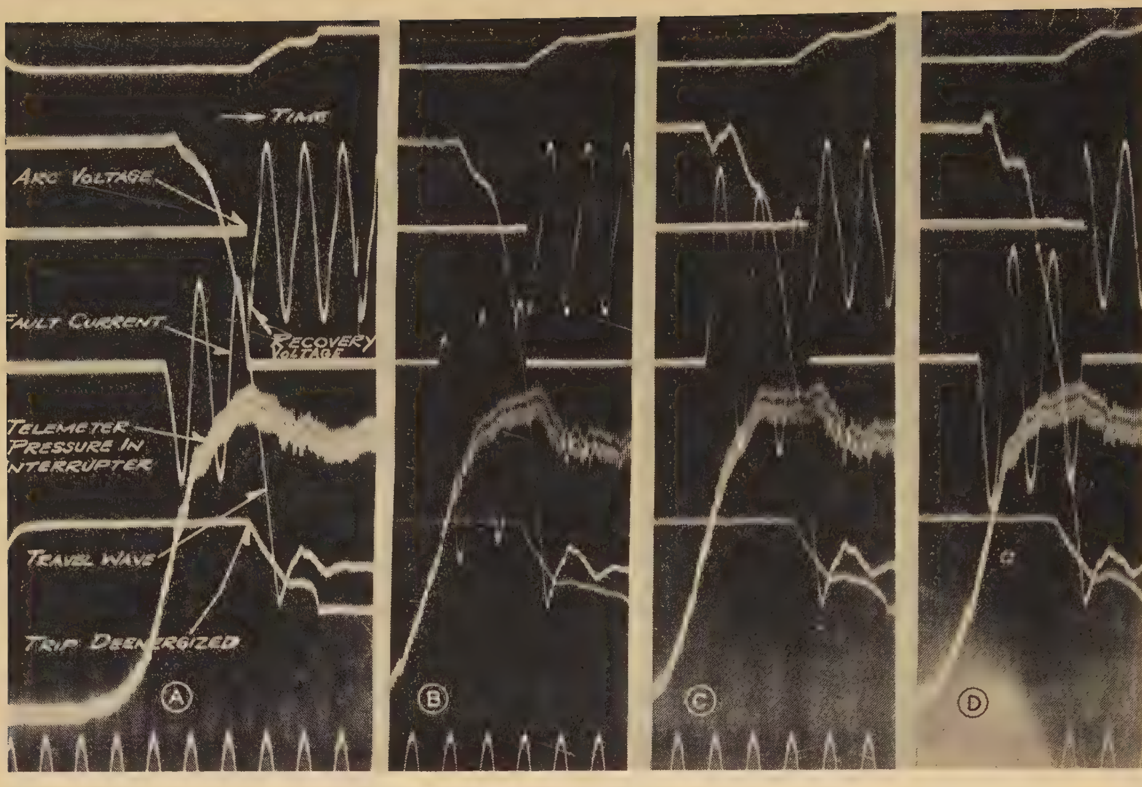


Figure 5. Magnetic oscillograms from table II. Current and voltage values noted are rms values per AIEE Standards

A—Fault current, 2,800 amperes. Recovery voltage, 65 kv

B—8,100 amperes, 64 kv

C—11,200 amperes, 63 kv

D—13,900 amperes, 62 kv

top. The disconnect is mechanically interconnected to the interrupting contact and both are operated by an air piston moving in a cylinder located in the pole-unit mechanism box. Air for operating this piston is transmitted from the tank through valves at ground potential, and thence through hollow porcelain insulators, one for closing and one for opening. These two porcelains with the third and larger one which carries the air blast from the tank to the interrupter, form a supporting tripod and the insulation to ground. The mechanical linkage between the operating cylinder, interrupting contacts, and disconnecting member are such that in normal service the disconnect opens last on an opening operation and closes first on a closing operation.

The interrupting contact consists of a simple rod which slides within two tulip-type contacts, one supported from the mechanism box and the other from the top of the breaker, both extending toward the interrupting element which is centrally located. The arc is drawn from the upper stationary contact, downwardly through the interrupter, where it is subjected to the air blast.

The breaker is ideal for high-speed reclosing duty because of efficient disposal of ionized gases from the interrupter and the high mechanical speed of the air-operating mechanism. In case of reclosure, the disconnecting switch is not opened; the contacts are simply parted in the air blast, the arc is interrupted and the contacts are reclosed before the air blast is turned off.

This type of construction provides porcelain insulation to ground of the current-carrying parts and air isolation between terminals when the breaker and disconnect are in the open position. There are no heavy operating rods with potential across them, since the entire mechanical effort is transmitted through the medium of air flow in the porcelain columns. Contacts, interrupter, and mechanisms are very accessible and easily maintained. Provision for a porcelain-

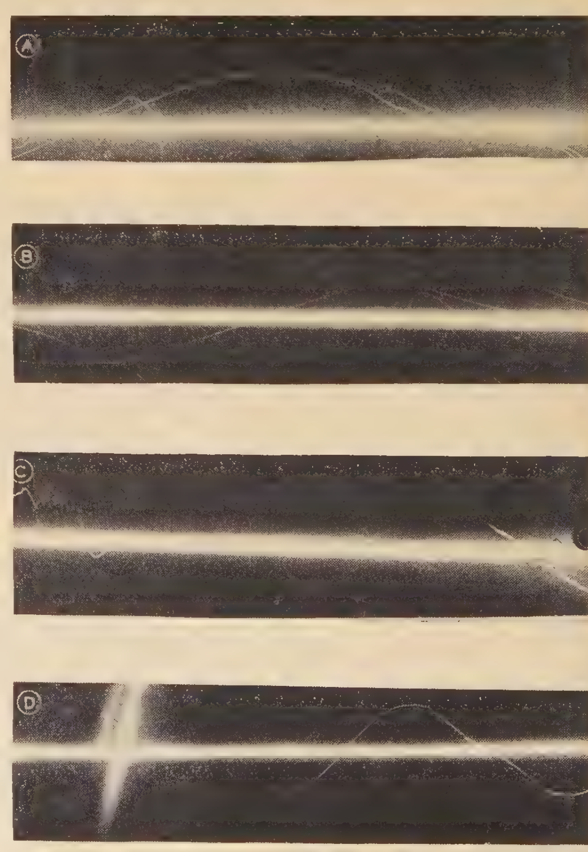


Figure 6. Cathode-ray oscillograms corresponding to those of figure 5

A—Fault current 2,800 amperes rms; restored voltage 65 kv. Oscillatory frequency 3,270 cycles per second; recovery rate 1,225 volts per microsecond. Maximum instantaneous voltage 157 kv

B—Fault current 8,100 amperes rms; restored voltage 64 kv. Oscillatory frequency 4,900 cycles per second; recovery rate 1,830 volts per microsecond. Maximum instantaneous voltage 124 kv

C—Fault current 11,200 amperes rms; restored voltage 63 kv. Oscillatory frequency 6,600 cycles per second; recovery rate 2,440 volts per microsecond. Maximum instantaneous voltage 135 kv

D—Fault current 13,900 amperes rms; restored voltage 62 kv. Oscillatory frequency 9,780 cycles per second; recovery rate 3,570 volts per microsecond. Maximum instantaneous voltage 135 kv

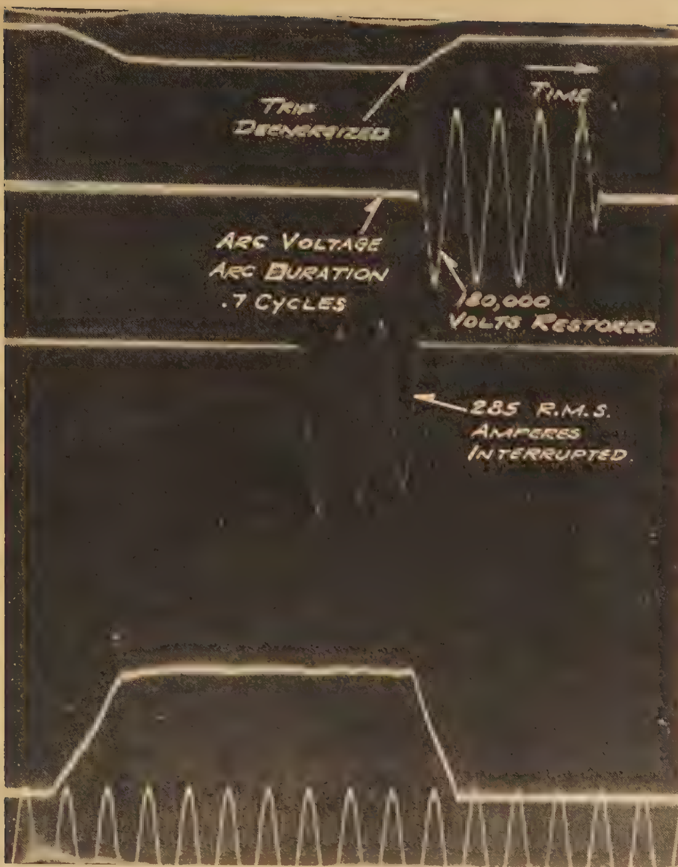


Figure 7. Magnetic oscillogram of 138-kv single-pole unit interrupting low current at 180 kv

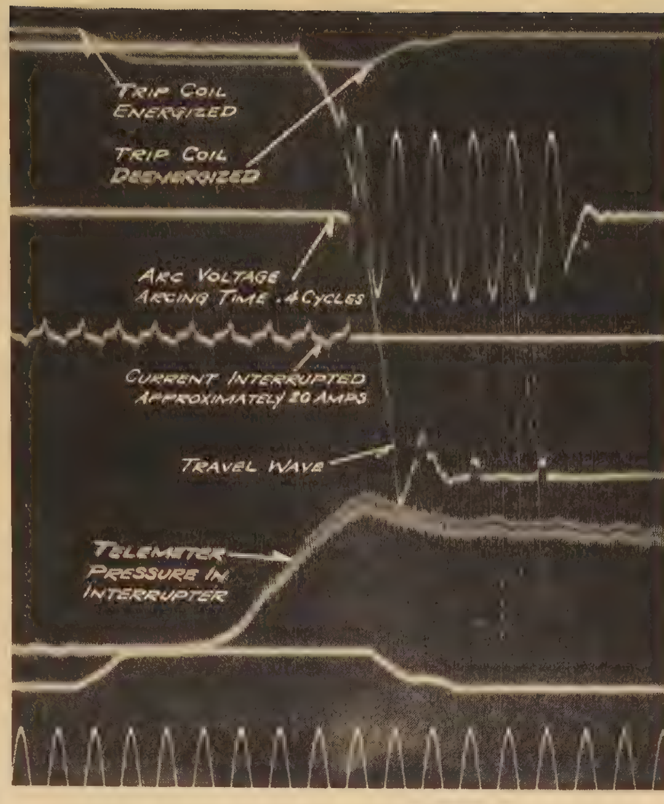


Figure 8. Typical interruption of transformer magnetizing current

clad current transformer is made on the disconnect end of the breaker. The pole units of a three-phase breaker are separate and distinct, and may be arranged for individual phase operation if desired. On the other hand, co-ordination of the three poles is possible by interlocking the air valves in obvious ways.

5. Experimental Test Results

Tables I and II show the results of two typical series of single-phase tests on the single-pole unit, 138-kv compressed air circuit breaker shown in figures 1 and 2. The highest of these tests represents power equivalent to slightly in excess of 2,000,000 kva on the basis of an ungrounded three-phase 138-kv system. The current on this film (figure 3) was unsymmetrical and thus contained considerable d-c component. On the basis that 127 kv is the line-to-neutral voltage of a grounded neutral system, the three-phase power equivalent is over 3,250,000 kva.[5,6]

Table I shows the results of a series of 18 tests at 132-kv applied voltage on the single-pole unit, 138-kv breaker at current values between 270 and 8,900 amperes. The restored voltage varied from 132 kv to 121 kv. The air pressure in the storage tank of the breaker varied from 210 to 230 pounds per square inch. The arcing time varied from 0.6 to 2.1 cycles. This variation indicates that in many of the operations even at 132 kv, the interruption was completed in the upper working unit without waiting for the arc to be drawn into the lower one. Figure 3 shows three typical oscillograms; one at 2,520, 5,840, and 8,900 amperes respectively. From the travel wave it is apparent that the 8,900 amperes was interrupted in the upper working unit which consists of one orifice and one contact, spaced less than one inch apart. Figure 4 shows the three cathode-ray oscillograms corresponding to the magnetic oscillograms in figure 3. The highest oscillatory frequency shown is 4,310 cycles per second, which occurred on the 8,900-ampere test. This corresponds to a recovery rate of 2,970 volts per microsecond. However, in table I frequencies as high as 4,620 cycles per second, or 3,180 volts per microsecond are recorded.

Table II shows the results of a series of tests at 66 kv and current values varying from 2,800 amperes to 13,900 amperes. Again all tests were single phase on the single-pole 138-kv unit shown in figure 2. The air pressure in the breaker storage tank varied from 210 to 230 pounds per square inch. The arcing time varied from 0.7 to 1.2 cycles. In all cases the circuit was interrupted without assistance from the lower working unit. Figure 5 shows the magnetic oscillograms for tests 1, 3, 5, and 7 of table II. Figure 6 shows the cathode-ray oscillograms corresponding to the magnetic oscillograms in figure 5. The oscillatory frequency of the 66-kv circuit was considerably higher than that of the 132-kv circuit. As recorded, these values varied from 3,270 to 9,780 cycles per second. This frequency resulted in a recovery rate which varied from 1,225 to 3,570 volts per microsecond, which is slightly in excess of that obtained on the 132-kv circuit when adjusted for minimum impedance.

Figure 7 shows the magnetic oscillogram of the upper working unit of the 138-kv breaker interrupting low current at 180 kv. Also, successful interruption of low values of current on a highly inductive circuit has been obtained up to 264 kv, but not until the arc was drawn into the second or lower working unit.

Figure 8 shows the magnetic oscillogram of the 138-kv pole unit interrupting the magnetizing current of two single-phase power transformers in parallel, each connected for 13.2 to 132 kv, 3.3 per cent impedance and 33,333 kva, giving a total current for both transformers of approximately 20 amperes. The circuit consisted of a 13.2-kv genera-

Table I. Opening Tests on an Experimental Compressed-Air Circuit Breaker

132-Kv Initial Voltage Applied to a Single-Pole Unit of a 138-Kv Circuit Breaker, 60 Cycles

Test Number	Recovery Voltage (Kv)	Amperes Interrupted	Tank Pressure	Arcing Time (Cycles)	Oscillatory Frequency (Cycles Per Sec.)	Test Transient Recovery Rate (Volts Per Microsec.)	Circuit Transient Recovery Rate (Volts Per Microsec.)
1	132	270	210	0.9			
2	130	910	210	0.8			
3	128	1,140	230	1.0			
4	124	1,340	230	1.0			
5	127	2,160	210	0.6			
6	126	2,290	230	0.6	2,430	1,700	1,750
7	123	2,520	230	1.2	2,600	1,750	1,880
8	123	3,200	230	2.1	2,170	1,865	2,000
9	123	3,300	230	1.4			
10	122	4,200	230	1.8	3,550	1,960	2,120
11	123	4,230	210	1.2			
12	122	4,570	230	0.8	3,280	2,010	2,170
13	123	5,600	220	1.2			
14	122	5,840	230	1.2	3,660	2,310	2,500
15	123	5,900	220	1.9	4,060	2,490	2,670
16	123	7,150	230	0.8	4,620	3,180	3,420
17	121	8,250	230	2.0	4,380	2,620	2,860
18	123	8,900	230	0.8	4,310	2,970	3,190

Table II. Opening Tests on an Experimental Compressed-Air Circuit Breaker

66-Kv Initial Voltage Applied to a Single-Pole Unit of 138-Kv Circuit Breakers, 60 Cycles

Test Number	RMS Amperes Interrupted	Cycles of Arcing	Restored Voltage	Air Pressure in Tank (Pounds Per Square Foot)	Circuit Oscillatory Frequency (Cycles Per Sec.)	Test Transient Recovery Rate (Volts Per Microsec.)	Circuit Transient Recovery Rate (Volts Per Microsec.)
1	2,800	0.7	65	210	3,270	1,225	1,243
2	5,500	0.8	65	210			
3	8,100	0.7	64	210	4,900	1,830	1,890
4	10,000	1.2	64	210			
5	11,200	1.0	63	210	6,600	2,440	2,550
6	12,200	0.8	64	210			
7	13,900	1.2	62	230	9,780	3,570	3,800

tor feeding a 13.2 to 132-kv transformer. In series with this transformer was the test breaker and the 132-kv windings of the unloaded transformers just described. Tests were made both with one and with two transformers for the load. In all cases the current was interrupted promptly in about one-half cycle, as shown in figure 8.

6. Conclusions

The general acceptance in this country of compressed air as an interrupting medium for low-voltage heavy-duty powerhouse breakers has stimulated interest in its application to outdoor high-voltage breakers.

Experimental evidence has shown that while the continuous current-carrying requirements and heavy interrupting duty of powerhouse breakers dictate a design using splitters and transverse flow, the vertical-flow type of interrupter may be employed to advantage for porcelain-clad outdoor high-voltage breakers.

Tests on a new type of vertical-flow interrupter indicate that it can be developed to handle the maximum kilovolt-ampere requirements at 69 kv and above. A comparison of table I and table II suggests that if approximately 14,000 amperes at 68 kv and 5,370 volts per microsecond can be successfully handled on one-half of the interrupter, currents considerably in excess of 8,900 amperes at 132 kv may be expected to carry this type of interrupter far into the future kilovolt-ampere requirements.

Bibliography

1. Structural Development of the De-ion Circuit Breaker up to 15,000 Volts, R. C. Dickinson and B. P. Baker. AIEE Transactions, volume 48, 1929, page 528.

2. A High Power Oilless Circuit Interrupter Using Water, W. M. Leeds. AIEE Transactions, volume 60, 1941 (February section), pages 85–8.

3. New 15-Kv Pneumatic Circuit Interrupter, L. R. Ludwig, H. L. Rawlins, B. P. Baker. AIEE Transactions, volume 59, 1940 (September section), page 528.

4. Displacement and Diffusion in Fluid-Flow Arc Extinction, J. Slepian. AIEE Transactions, volume 60, 1941 (April section), pages 162–7.

5. Multiple-Grid Breakers for High Voltage Service, J. B. MacNeill and A. W. Hill. AIEE Transactions, volume 58, 1939 (August section), pages 427–31.

6. The Vertical Flow Interrupter and Its Application to Oil-Poor Circuit Breakers, B. P. Baker. AIEE Transactions, volume 60, 1941.

Development of the Glow-Switch

R. F. HAYS
ASSOCIATE AIEE

THE glow-switch[1] is an automatic switch for starting fluorescent lamps.[2] It is unique in that it is a thermal switch without a heater element, the heat being supplied by a glow discharge. The glow-switch functions as a time-delay relay yet it is a single-element switch with only two leads. At one value of applied voltage its resistance becomes a fraction of an ohm, while at a voltage only slightly lower, its resistance is measured in megohms. Before proceeding with the story of the development of the glow-switch, it is in order to discuss briefly the task which it performs.

Once the discharge is started, a fluorescent lamp can be operated from an a-c supply whose voltage is approximately twice lamp voltage. The lamp must be operated in series with an impedance, usually an inductance, to limit the current.[3] The most commonly used circuit is shown in figure 1. A voltage considerably higher than the supply voltage is necessary to start the discharge. The discharge should not be started until after the lamp cathodes have been heated to a temperature at which they can emit the necessary supply of electrons without entailing excessive positive ion bombardment. The glow-switch serves to automatically connect the lamp cathodes in series until they are heated to operating temperature, and then to break the connection, and subject the lamp to a transient voltage sufficiently high to start the discharge.

The glow-switch, figure 5, consists of a glass bulb, filled with an inert gas and containing a pair of contacts operated by thermostatic bimetal. Initially the contacts are open and the supply voltage appears across the switch. The supply voltage is sufficient to establish in the switch a glow discharge which heats the bimetal and causes the contacts to close. The current passed by the glow discharge is only a few milliamperes and does not cause any appreciable heating of the lamp cathodes, but when the contacts close, the current is limited only by the series inductance and the resistance of the cathodes. The cathode-heating current is approximately $1^1/_2$ times normal lamp current and it quickly heats the cathodes to operating temperature. While the contacts are closed, the glow discharge is extinguished so that the bimetal cools and after a short-time delay, during which the lamp cathodes are heated, the contacts open. Opening of the contacts suddenly interrupts the current and induces in the series inductance a transient voltage sufficiently high to start the arc through the lamp. After the lamp is started the cathodes are self-heating and the voltage across the lamp is insufficient to re-establish the glow discharge in the switch. The contacts remain open and the switch consumes no energy. If for any reason the lamp does not start the first time the contacts open, the cycle is quickly repeated.

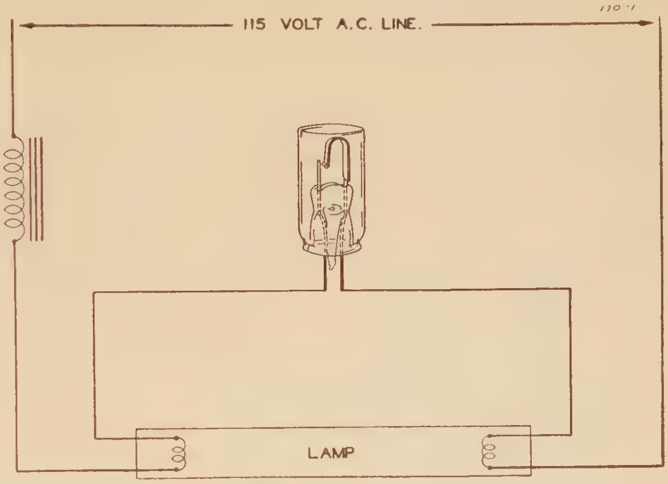


Figure 1. Fluorescent lamp circuit

The requirements that must be met by the glow-switch are as follows:

(1). The breakdown voltage for the glow discharge must be less than supply voltage and greater than lamp voltage.

(2). The contacts must close quickly.

(3). The contacts must remain closed for a period of time sufficient to allow the lamp cathodes to reach operating temperature.

(4). The switch must interrupt the current quickly so that the transient voltage induced in the series inductance will be sufficiently high to start the lamp.

(5). The switch must be small and inexpensive.

Breakdown Voltage

The breakdown voltage, or the voltage at which the glow discharge starts, must be less than the lowest supply voltage with which the glow-switch is to be used, and must be safely above peak lamp voltage so that the switch will not glow and the contacts will not close after the lamp starts. The *T*-12, 15-watt, the *T*-8, 15-watt, and the *T*-12, 20-watt lamps operate at 48, 56, and 62 volts respectively, and all three lamps are for operation from a supply of 118 volts ± 10 per cent. The same glow-switch is used with all three lamps. The voltage wave form for a fluorescent lamp is nonsinusoidal, and at low current the voltage is abnormally high. The peak voltage for a 20-watt lamp operating from minimum allowable supply voltage is equal the peak value of a sinusoidal voltage of 70 volts. Accordingly, the minimum breakdown voltage was set at 75 volts alternating current, and the voltage necessary to start the glow discharge and cause the contacts to close in a reasonable time was set at 105 volts.

It was found that neon containing a small amount of argon, used with electrodes coated with magnesium, gave a minimum breakdown voltage just greater than the minimum allowable limit. The breakdown voltage should not vary greatly with respect to gas pressure, gas mixture, or electrode separation, so that reasonable tolerances can be allowed in manufacture, and so that breakdown voltage will be relatively independent of pressure changes due to gas cleanup during the life of the switch. Curve *A* of

Paper 41-70, recommended by the AIEE committee on production and application of light, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 28, 1940; made available for preprinting December 14, 1940.

R. F. Hays is vapor lamp development engineer for the Westinghouse Electric and Manufacturing Company, Bloomfield, N. J.

Credit for development of the glow-switch to its present form is shared by D. S. Gustin, W. E. Carpenter and the author, all of whom are members of the engineering department, vapor lamp development section, of the Westinghouse lamp division at Bloomfield, N. J.

1. For all numbered references, see list at end of paper.

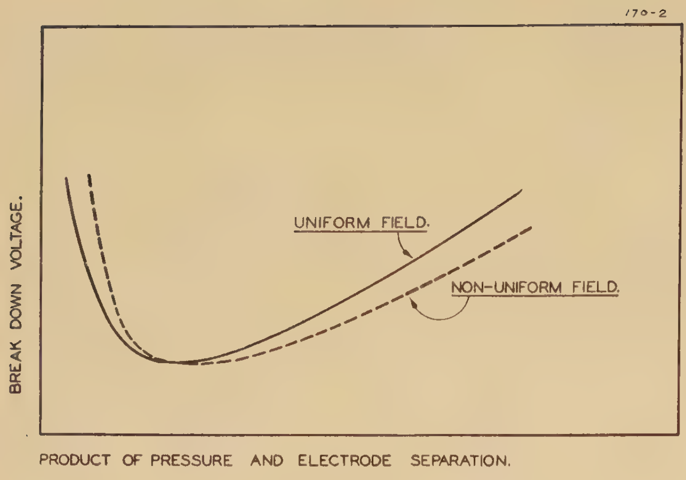


Figure 2. Breakdown voltage

With respect to gas pressure and electrode separation for (*A*) parallel plane electrodes, and (*B*) irregularly shaped electrodes (Slepian)

figure 2 shows how breakdown voltage varies with respect to the product of gas pressure and electrode separation for a glow discharge between plane parallel electrodes.[4] Curve *B* shows the effect of a nonuniform field obtained by using electrodes of irregular shape. Fortunately, a nonuniform field makes the break-down voltage less dependent upon the product of pressure and electrode separation at values greater than that corresponding to minimum breakdown voltage. Figure 3 shows that the addition of a small amount of argon to the neon lowers the breakdown voltage and makes it less dependent upon pressure.[5] The use of irregularly shaped electrodes and of neon containing a small amount of argon makes the breakdown voltage practically independent of pressure or electrode separation over a wide range. Breakdown voltage with respect to the per cent of argon added to the neon[5] is shown in figure 4. One-half of one per cent argon was added to the neon so that relatively large deviation from the specified amount of argon would have no serious effect on the breakdown voltage.

Fast Closing of the Contacts

The contacts can be made to close quickly by the use of a sensitive bimetal element, by using closely spaced contacts, by using a bimetal element with minimum heat capacity, and by producing a high-current density at the surface of the bimetal when it serves as cathode for the glow discharge. Sensitive bimetal and close contact spacing result in closure of the contacts upon a slight rise in temperature. The temperature of the bimetal necessary for closing the contacts should be as high as 100 degrees centigrade, so that operation will be relatively independent of room temperature. A sensitive bimetal element is necessarily long and thin, and consequently, the force per unit deflection of the contact is small. If the bimetal element is sensitive and the contact spacing is small, there will be little force available to pull the contacts apart when they stick. The bimetal should be short and only as thick as necessary to obtain the required rigidity so that the heat capacity will be low. The most desirable method of increasing speed of operation is that of increasing the current density.

For a normal glow discharge the cathode-voltage drop and the current density at the surface of the cathode are constant, and the current density is proportional to the square of the gas pressure. The size of the cathode spot increases, but the cathode drop remains constant as the current is increased until the cathode is completely covered by the glow. Further increase in current demands an increase in current density at the cathode surface, and causes an increase in cathode-voltage drop. Such a condition represents an abnormal glow discharge.

Slepian[4] has given the following equation for current density for an abnormal glow discharge:

$$J = J_0 + K(E - E_0)^2 P^2 \qquad (1)$$

$$J_0 = BP^2 \qquad (2)$$

where J is current density; J_0, normal current density; E, cathode drop, E_0, normal cathode drop; P, gas pressure; and B and K are constants. This equation shows that to cause rapid closing of the contacts by producing a high-current density, the gas pressure must be high, E_0 must be as low as permissible, and E must be high. For a neon-argon mixture in a nonuniform field, and PD greater than the critical value, E_0 is practically equal the breakdown voltage, the value of which has already been determined. E is equal the supply voltage minus the IZ drop in the inductance and the lamp cathodes. Obviously, E will be a maximum only if the current drawn by the glow discharge is a minimum. A high-current density and yet a small current can be obtained only by the use of a small cathode-surface area. Then, for rapid closing of the contacts, the gas pressure must be high, and the bimetal element must be as small as is practical from the standpoint of manufacture.

Time Delay

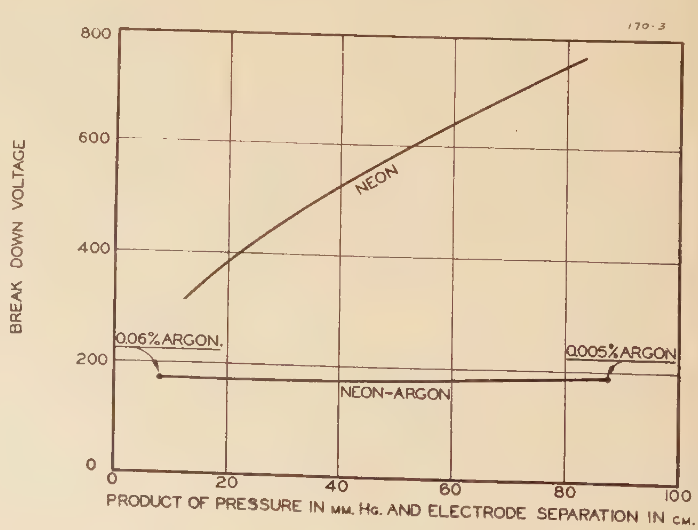
The contacts must remain closed for a period of time sufficient to allow the lamp cathodes to reach operating temperature. For 15- and 20-watt fluorescent lamps this time is approximately one second. The time delay is produced by the inevitable sticking of the contacts and by nonuniform heating of the bimetal, which results from the use of high gas pressure.

Transient Voltage for Starting the Lamp

When the contacts open, there must be induced in the series inductance a transient voltage of sufficient magnitude and duration to start the lamp. It is impos-

Figure 3. Breakdown voltage

With respect to gas pressure and electrode separation for pure neon and for a mixture of neon and argon (Penning)



sible to interrupt a current through an inductance instantaneously. For an instant after the contacts open, the inductance forces the current to continue flowing at a value practically equal to that of the instant before the contacts opened. The current continues to flow and decreases in magnitude as the energy stored in the magnetic field of the series inductance is dissipated. Then, until the lamp starts, the voltage across the glow-switch and across the lamp is the voltage corresponding to the current flowing through the switch whose contacts are open. Current can continue flowing through the switch after the contacts separate because of arcing at the contacts and re-establishment of the glow discharge. As the contacts separate, the current is carried by one point on each contact and the temperature of these points reaches the value which Slepian[6] has shown to be equal

$$T = \frac{E^2}{33.5kp} \tag{3}$$

where k is the thermal conductivity of the contact material (calories/centimeters squared/degrees centigrade/centimeters) and p is the electrical resistivity of the contact material (ohms/centimeters cubed). Copper contacts interrupting a one-volt circuit reach a temperature of approximately 4,000 degrees. Obviously, there is no metallic contact material available which will not melt and vaporize at the voltage to be used. Arcing at the contacts is supported chiefly by thermionic emission from the hot points and by thermal ionization of the hot vapor emitted from the points. Arcing can be kept at a minimum by using contact material which evolves a minimum amount of vapor. Tungsten makes an ideal contact because of its high work function, high melting point, low vapor pressure even in the molten state, and high resistance when hot. The current due to arcing at the tungsten contacts is negligible compared with that due to re-establishment of the glow discharge. Therefore, the transient voltage is practically equal the voltage across the glow discharge corresponding to the instantaneous value of current through the circuit.

Figure 5. The glow-switch, assembly of glow-switch and capacitor for suppressing radio interference, and the complete starter unit

Rearrangement of equation 1 shows that the voltage across the glow discharge is equal

$$E = E_0 + (J - J_0)^{1/2} \frac{K}{P} \tag{4}$$

where

$$J = \frac{i}{A} \tag{5}$$

Equation 4 shows that the transient voltage can be made high by the use of low gas pressure. It has already been shown that the pressure must be high if the contacts are to close quickly. A compromise must be made. The pressure should be made only as high as is necessary for the contacts to close in a reasonable length of time; say, one or two seconds. Even so, the transient voltage is not always high enough to insure reliable starting of the lamp. Since E_0 and J_0 have already been fixed, the only other expedient is to increase the value of J.

Equation 5 shows that J can be made large by reducing the value of A. Fortunately, as has already been shown, A, the surface area of the cathode for the glow discharge, should be small to permit quick closing of the contacts. With the bimetal as small as is practical from the standpoint of manufacture, its surface area is still too large to insure reliable starting of the lamp. It is necessary further to increase the value of J by using only one strip of bimetal and letting the other electrode for the glow discharge consist of only a short lead wire with a contact welded to it. The surface area of this short lead wire and contact can easily be made very small. Of course, the highest transient voltage is produced only if at the instant the contacts separate, the current is flowing in the direction that will cause the small surface area electrode to serve as cathode for the glow discharge. The fact that there is only a 50 per cent probability that the highest transient voltage will be produced is not considered objectionable because, if the voltage is insufficient to start the lamp, the energy stored in the series inductance is instantly dissipated in the glow switch, and the contacts immediately reclose to repeat the cycle. The value of the series inductance has little effect upon the magnitude of the transient voltage but does affect its duration. Equations 4 and 5 are only approximately true[7] because the transient voltage varies too rapidly for the glow discharge to reach equilibrium. However, they show what steps must be taken to improve the characteristics of the switch.

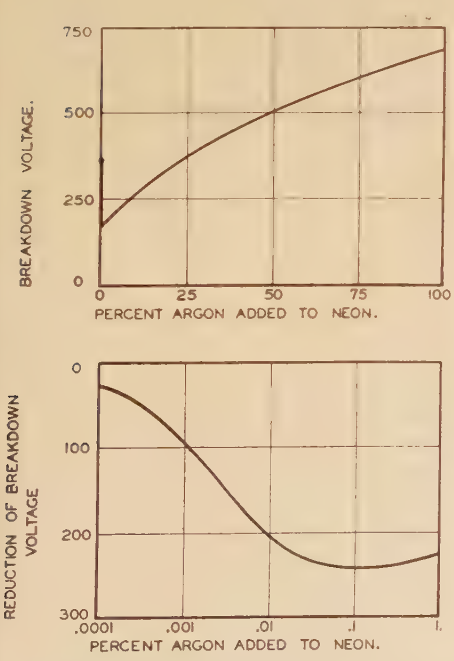


Figure 4. Minimum breakdown voltage for neon with respect to the percentage of added argon (Penning)

Conclusion

It has been shown that for proper operating characteristics, the glow-switch necessarily must be small. The small size and simple construction of the switch as shown in figure 5 lend it to economical production on automatic machinery.

A glow-switch will start a lamp under normal conditions approximately a mil-

The Protective Link

J. K. HODNETTE
MEMBER AIEE

M. G. LEONARD
ASSOCIATE AIEE

Synopsis: The protective link is a device recently developed for internal mounting in transformer of a wide variety of types and ratings. Its most common application, however, is in distribution transformers where it serves to disconnect the transformer in case of internal fault. Its action in arc extinction depends on a number of factors including a novel arrangement of the lower terminal which allows it to be expelled from the link when heavy currents are interrupted.

Although simple and compact, the link is a very efficient arc-quenching device, and has a remarkably high-circuit interrupting capacity combined with high speed of operation. Power arcs of more than 250,000-kva single phase have been interrupted in one-half cycle.

Introduction

SOME form of circuit-opening means has been used with transformers from the very beginning of the a-c system for the purpose of protecting the line or system against an extended outage in case of damage to an individual transformer. Economic factors in general have dictated the kind or type or the extent of the protection. Large important substations are protected with circuit breakers and differential-transformer protection to remove quickly a faulted transformer. Less important substations are protected by circuit breakers actuated by overcurrent or ground relays, and finally where circuit breakers cannot be justified from the standpoint of cost, high-voltage fuses are used to protect smaller substations, transformer banks, and individual transformers. Recently protective links have been applied to transformers for a similar purpose. They have been used on a wide range of ratings, but it is in the distribution range where they have found most of their application up to the present time.

In this application they are used in conjunction with circuit breakers to permit loading the transformer to its maximum safe copper temperature regardless of the amount or duration of load. The link alone, though designed for long-time lag, will not serve this purpose, because of the extremely long time constant of the transformer. The circuit breaker, on the low voltage side, follows this characteristic of the transformer and effectively prevents it from burnout because of overload. The protective link, on the high voltage side, protects the line from outage which might occur in case of failure within the transformer. In this function, its construction and mounting provide a number of inherent advantages. It is electrically protected against false operation by the transformer breaker on the one side and by sectionalizing or line breakers on the other. It is mechanically strong, and resistant to the action of transformer oil. Because of its internal mounting it is not exposed to weathering, and because of its electrical connection at the transformer bushing it is not subjected to lightning surges. These factors are especially important on the smaller ratings where the physical size of the fusible element is necessarily very small.

Paper 41-59, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 26, 1940; made available for preprinting December 13, 1940.

J. K. HODNETTE is manager of transformer engineering department, and M. G. LEONARD is electrical engineer for the Westinghouse Electric and Manufacturing Company, Sharon, Pa.

Description of the Protective Link

The appearance of the link as used in distribution transformers is shown in figure 1. This shows a core and coil assembly with a protective link mounted at each side of the porcelain tap-changer block. When assembled in the transformer, the high-voltage bushing lead runs directly to the top terminal on the link, thus placing the link electrically ahead of any fault which may occur either in the coil or the tap changer. The link itself is shown in section in the drawing of figure 2. It is simple in construction, consisting essentially of a fusible element enclosed in an insulating tube with a fixed and a movable terminal. The movable terminal, mounted at the

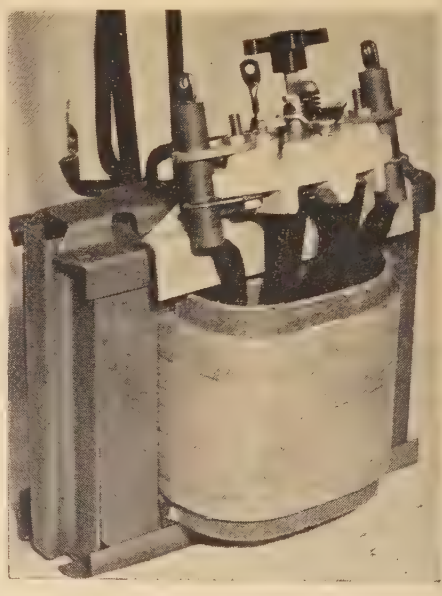


Figure 1. Protective links mounted on core and coil assembly for distribution transformers

---

lion times, so that its life ordinarily should be very long. However, when a lamp fails, the switch keeps operating in an attempt to start it. Under failed lamp conditions, the life of the switch is approximately 100 hours.

In addition to starting lamps under conditions which insure good lamp life, the glow-switch has a number of advantages over other types of starters. It is operative over a wide range of current and compared with other types of lamp starters, it has a very long life under failed lamp conditions. Because the glow-switch is a two-wire device, it reduces wiring to a minimum. Simplified wiring permits placement of the glow-switch in a removable capsule which fits into an extension of the fluorescent lamp socket. Field results with the glow-switch, since its introduction two years ago, have been very satisfactory, and at present there are approximately six million glow-switches in use.

Bibliography

1. AN ELECTRONIC SWITCH FOR STARTING FLUORESCENT LAMPS, R. F. Hays. *Electronics*, May 1940, page 14.

2. AN ELECTRONIC RELAY FOR INITIATING VAPOR DISCHARGE, E. C. Dench. ELECTRICAL ENGINEERING, volume 59, November 1940, page 461.

3. ALTERNATING CURRENT CIRCUITS FOR FLUORESCENT LAMPS, R. F. Hays and D. S. Gustin. *Transactions* of the Illuminating Engineering Society, December 1940, page 939.

4. CONDUCTION OF ELECTRICITY IN GASES (book), J. Slepian. Educational Dept., Westinghouse Electric and Manufacturing. Co., Course No. 38.

5. UBER DEN EINFLUB SEHR GERINGER BEIMISCHUNGEN AUF DIE ZUNDSPANNUNG DER EDELGASE, F. M. Penning. *Zeitschrift Fuer Physik*, volume 46, page 335.

6. TEMPERATURE OF A CONTACT, J. Slepian. JOURNAL OF THE AIEE, volume 45, October 1926, page 930.

7. DYNAMIC CHARACTERISTICS OF GLOW DISCHARGE TUBES, H. J. Reich and W. A. Depp. *Journal of Applied Physics*, volume 9, June 1938, page 421.

lower end of the tube, is one of the new features of this design, and plays an important part in extinguishing the arc, as explained below. The fusible element consists of a mechanically strong wire which is chemically neutral in transformer oil and resistant to corrosion; these properties are essential to insure stability of the fusing characteristic over a long period of time. The fusible element is composed of copper, or, for the smaller size, a high-resistance copper alloy. The fusing temperature is much in excess of the boiling temperature of the oil. This is an important characteristic, for it tends to reduce the damage to the link caused by momentary overcurrent, and provides a means for control of the fusing-time curve of the link as described below.

Surrounding the fusible element (figure 2) is a small insulating tube, the purpose of which is to retard the flow of heat from the wire. When a current slightly above the minimum fusing value is passed through the wire, its temperature is increased depending upon the rate of heat generation in the conductor and the rate of heat dissipation into the oil. With the current constant, the temperature increases approximately exponentially until the boiling temperature of the oil is reached. The chemical change in the oil under these conditions greatly increases the rate of heat dissipation of the

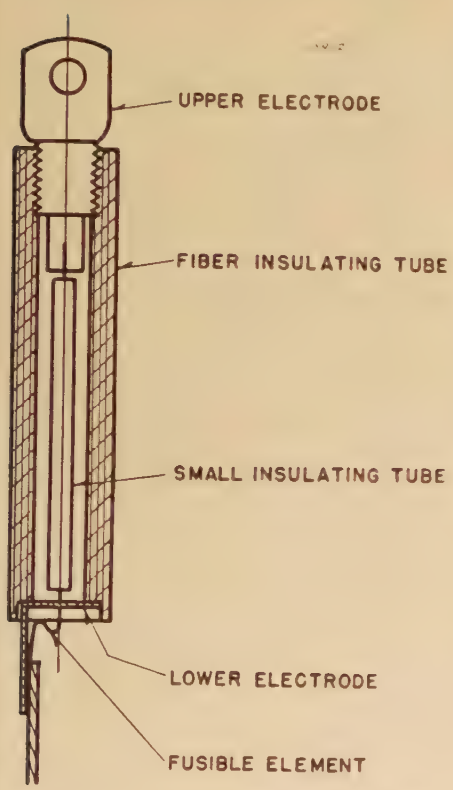


Figure 2. Section through protective link

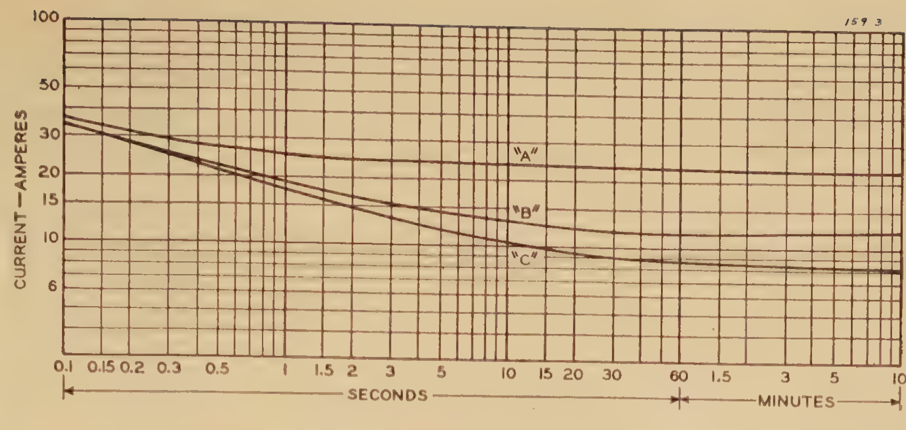


Figure 3. Fusing characteristic of protective links

(*a*)—Bare conductor in oil
(*b*)—Small insulated tube over conductor
(*c*)—Small insulated tube over conductor and gas entrapped within link

oil. As a result, little further change in temperature results until the distillation gases sufficiently blanket the conductor. The temperature again increases approximately exponentially until the fusing point is reached.

If a bare conductor placed in the oil were to be used as a protective link, the gases distilled from the oil would escape freely and the current-time fusing characteristic of the conductor would be quite flat as shown in curve *A*, figure 3. By surrounding the link with a small insulating tube, the distillation gases quickly displace the oil in the tube and it then effectively insulates the conductor and retards the heat flow. This reduces the current and the time required to fuse the conductor for all ranges of current and time beyond that where all heat is stored in the conductor. An example of the reduction in current is shown in curve *B*, figure 3. By controlling the blanketing action of the distillation gases, the shape of the current-time curve can be adjusted to the desired shape to co-ordinate most effectively with other current-limiting devices on the system. The maximum blanketing occurs when the conductor is entirely surrounded by a gas (curve *C*, figure 3).

With the present knowledge of the impulse characteristics of transformer insulation and with modern lightning protective devices arranged for balanced lightning protection, major insulation failures from lightning have been practically eliminated. Therefore, line-to-line or line-to-ground failures of transformers in service, which would make it necessary for the protective links to open the full short-circuit current of the system, are uncommon. To insure successful operation, however, the protective links should be selected with sufficient arc-interrupting capacity to interrupt the current resulting from a short circuit across the terminal board of the transformers.

This, as mentioned, is not the usual condition. One of the most usual causes of transformer failure is short circuit in one of the windings between turns or between coils. Under these conditions, the fault current builds up spasmodically with a rush of current as each new element of the winding is involved in the failure. Since a considerable portion of the trans-

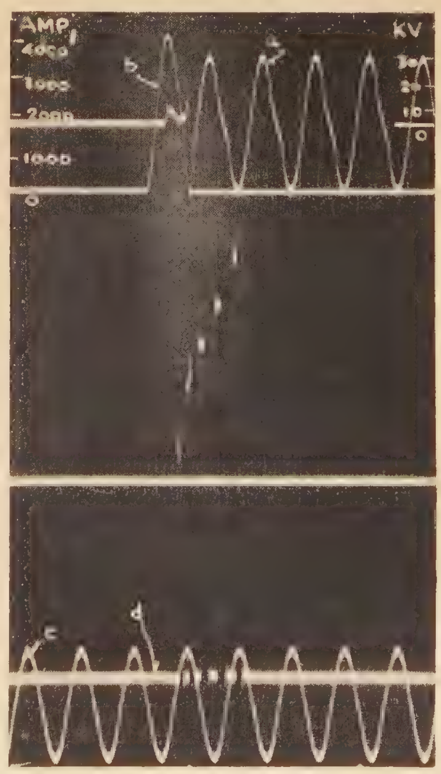


Figure 4. Oscillogram of protective link operation showing

(*a*)—Voltage across link
(*b*)—Current through link
(*c*)—Timing wave
(*d*)—Position indicator wave

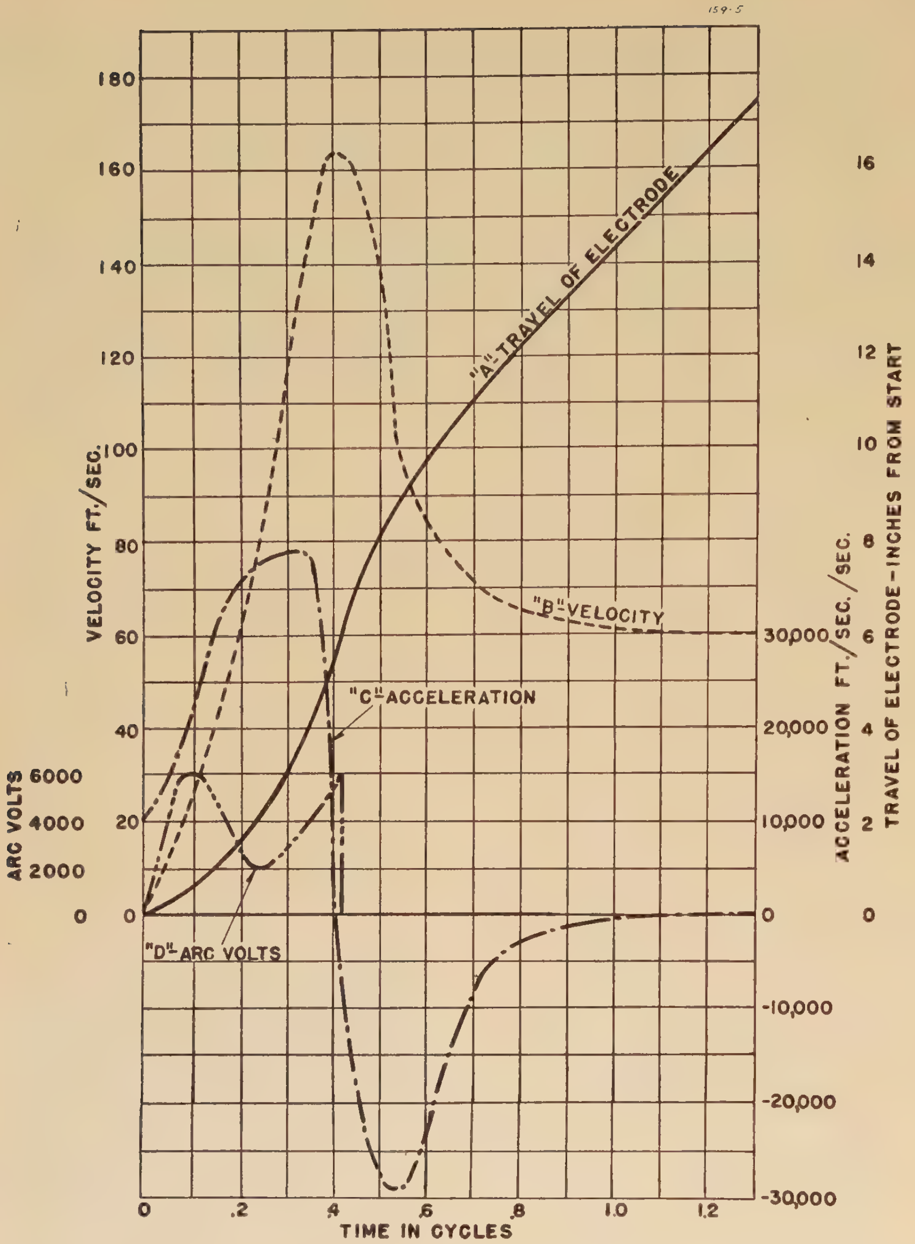


Figure 5. Analysis of electrode travel during arc interruption

former-winding impedance remains in series with the fault, the current builds up to a value sufficient to blow the protective link but does not approach system short-circuit proportions.

At the time of trouble in actual service, when the current reaches a value sufficient to fuse the link, an arc is formed in the oil inside the fiber-insulating tube. A high pressure is immediately developed inside the tube which increases the arc-voltage drop and aids in quenching the arc. This high pressure drives the lower electrode violently from the tube as if by explosive action. The arc trailing after it passes from the high-pressure area inside the tube to an area of comparatively low pressure outside the tube. This is an area of violent turbulence which is effective in arc quenching, principally because of the diffusion of the oil into the gas bubble surrounding the arc. Finally, the movable electrode moves rapidly through the oil stream tending to "neck" the arc and quench it.

Interruption of fault current occurs usually at the first current zero after the arc has been struck. The rapid movement of the free terminal through the oil builds up a layer of fresh oil between the moving electrode and the gas bubble after current zero, which effectively prevents restriking. Mounting the link in a vertical position so that the free electrode moves downward aids in this respect since the gas bubble is displaced upward by the pressure of the oil.

In order to investigate the action which takes place during the operation of the protective link, a special test was set up. A link was made in which the lower electrode was carried on a light but rigid arm. This arm was pivoted at one end, to allow the electrode to swing down freely as it does when attached to a flexible cable. A commutator device was mounted on the arm to permit recording of its position on an oscillograph.

The action of the link in interrupting the arc and a conception of the speed and the forces involved can be obtained from the results of this test as shown in figures 4 and 5. Figure 4 is an oscillogram of an interruption of a circuit connected for 1,500 amperes and 22,000 volts. It shows the normal operation of clearing the circuit in one-half cycle, and also shows very clearly the eight make-and-break points obtained by the commutator (curve D, figure 4).

From these data, a curve of position of the electrode against time is obtained, as shown in figure 5, curve A. Graphical analysis of this curve for slope gives the velocity of the electrode, curve B. In the same way, analysis of curve B gives the acceleration curve C. The curve of arc voltage D is also shown.

These curves indicate the following:

1. The electrode travels approximately six inches during the arcing period.
2. The maximum velocity is reached at the end of the arcing period; in this case it is approximately 165 feet per second.
3. The maximum acceleration occurs just after the electrode leaves the tube; in this case it is approximately 40,000 feet per second per second.
4. The electrode travels approximately eight inches through oil in the half cycle following the extinction of the arc.

Application

The choice of a protective link for a particular application depends upon the voltage and the current to be interrupted. The simple link shown in figure 1 has been supplied extensively to a completely self-protected distribution transformer, and other distribution transformers exposed to severe lightning conditions. Its interrupting ability is adequate for practically all applications for transformers up to 100 kva and 15,000 volts. These links will interrupt successfully 12,000 to 20,000-kva single phase in the above voltage range.

For larger units in the range of approximately 20,000 to 75,000-kva single-phase interrupting capacity, a longer and stronger fiber tube is necessary. A protective link of this type is shown in figure 6. The general construction remains the same. It will be noted, however, that the lower electrode is not attached to the tube, but is suspended from the fixed

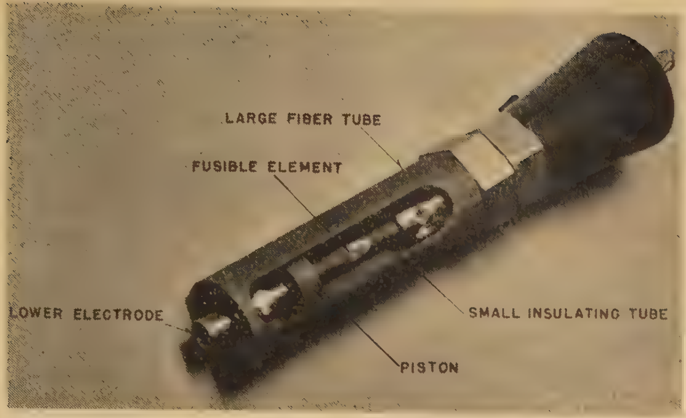


Figure 6. Protective link for application to power transformer

electrode. A piston of insulating material is used to transmit the mechanical impulse to the movable electrode. Protective links of this rating have been applied to completely self-protected power transformers in sizes up to 3,000 kva and 33,000 volts.

Another interesting application is to subway distribution transformers. Links with an arc-interrupting capacity of 10,000 amperes were applied to 2,400-volt subway transformers. These transformers were equipped with thermally-operated breakers in the secondary, properly coordinated with the protective links and arranged to protect the units against burnout from overload and secondary short circuit. The use of the protective links together with a disconnecting-type, high-voltage cable connection made the unit self-contained and very easy to install.

For application to still higher capacity circuits, the protective link is modified as shown in figure 7. Means are provided to reduce the pressure produced inside the tube and to increase the arc-quenching action at low currents and high voltages. The reduction in pressure is accomplished by enlarging the space above the main insulating tube and mounting inside it a shock-absorbing device. This device consists of a thin-walled cylindrical ring filled with gas under atmospheric pressure. Under high-current operation, the walls of the gas container collapse and cushion the pressure wave, thereby reducing the mechanical shock and the internal pressure in the device.

Interruption of low currents at high voltage is accomplished by means of the small auxiliary fiber tube. This tube creates a high-pressure zone immediately surrounding the arc, making it effective for currents as low as the exciting current of the transformer. At high current this tube is ruptured.

Links of the type as shown in figure 7 are applied to transformers with voltage ratings up to 69,000 volts. They have been tested at power levels of more than 250,000-kva single phase. An example of this is shown on the oscillogram of figure 8.

Field Experience

Within the last few years many thousands of protective links have been placed in service in distribution transformers. Some of these have had occasion to operate either because of a defect in the winding causing coil failure, or because of low electrical clearance at some point causing breakdown on surge. In most cases the lower electrode was driven from the end of the tube. Occasionally, when the current was only slightly above the minimum required to fuse, the arc was quenched before the electrode was dislodged. Usually the electrode was found to be driven out violently; in fact the evidence of the violence of this action is some indication of the magnitude of the current interrupted. But even when severe mechanical damage was done, the link served to clear the circuit, and the small amount of burning on the electrodes showed that the arc was extinguished quickly.

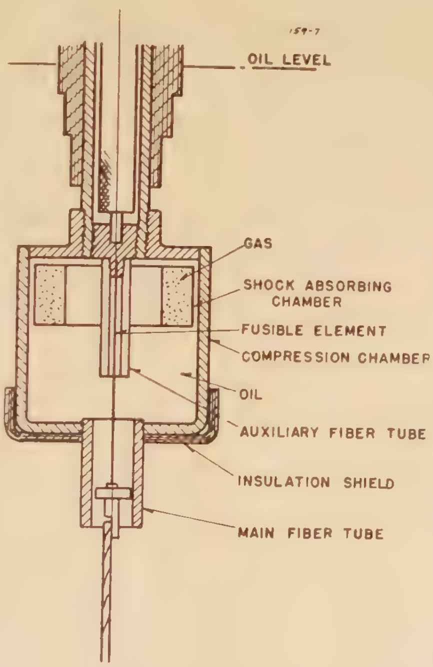


Figure 7. Protective link for high-current and high-voltage interrupting capacity

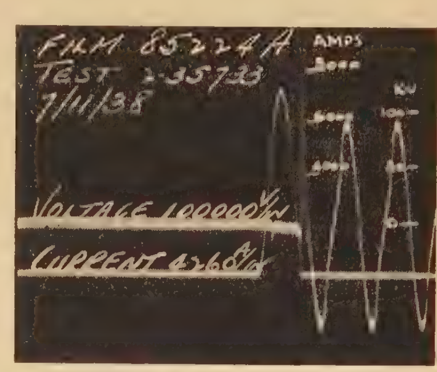


Figure 8. Oscillogram of protective link operation for link shown in figure 7

A case of operation on power transformer has occurred. Links were applied to the high-voltage side of a 33,000 to 4,160 volt, 1,000-kva 3-phase unit, and a breaker was connected on the low-voltage side. This breaker was rated at 5 kv, and protected by 33-kv links connected in series. This was considered desirable because high- and low-voltage lines were carried on the same pole. Shortly after this unit was put into operation, a wind storm blew off a sheet metal roof from a barn which struck the line, broke the high-voltage wires and caused them to fall across the low-voltage line. The breaker opened, but was not able to clear the high-voltage arc, which burned across the open contacts until the protective links cleared the circuit. Two of the links on the low-voltage side and one on the high-voltage side were blown during this disturbance. Except for the burning of the breaker contacts and adjacent parts, no damage was done to the unit. After reloading the links, the transformer was put back on the line and has since functioned satisfactorily.

Variations of Atmospheric Temperature With Altitude in the United States

H. W. TENNEY
MEMBER AIEE

IT has long been recognized that with increase in altitude the density of air decreases and influences the voltage rating and temperature rise of electrical apparatus. However, different standards for apparatus do not give the same weight to these factors. Examination of Weather Bureau data shows that there is a decrease in average atmospheric temperature with altitude, which should compensate to some extent for the influence of the decrease in air density on the rate of cooling at higher altitudes. This led to a study of temperature records of the United States for the purpose of presenting a summary of the variation of mean temperature with altitude.

The Weather Bureau of the United States is to be complimented on the fund of data which it has collected and the usable form in which it is available. The chief source of data used in this paper is the 1938 issue of Climatological Data for the United States.[1] In this issue there are temperature data from 3,119 stations for the year 1938 and the departure of the annual mean temperature from the mean of the temperature for all years of record. Consequently, by algebraic subtraction of the departure of the mean for 1938 from the annual mean, the mean temperature for the period of record is obtained.

The daily maximum and minimum temperatures are read from properly exposed thermometers at the co-operative observation station. At the first-order Weather Bureau stations thermograph charts are taken, giving continuous record of temperature variations. The records made by co-operative observers of the Weather Bureau, which are used largely in preparing charts and drafts, are made with standard maximum and minimum thermometers exposed in approved shelters, usually at an elevation of five feet above the ground. The true average daily temperature corresponds closely to the average of 24 hourly observations, but as several other combinations of hourly values give averages that differ but little from the true daily average some one of these is generally used to reduce observationa' work. The combination—

$$\frac{(7 \text{ a.m.}+2 \text{ p.m.}+9 \text{ p.m.}+9 \text{ p.m.})}{4}$$

gives a value which differs only slightly from the true daily average, and

$$\frac{(\text{sunrise}+2 \text{ p.m.}+9 \text{ p.m.})}{3}$$

also gives fairly accurate results. The formula

$$\frac{(\text{maximum}+\text{minimum})}{2}$$

is easy of application and very satisfactory when dependable maximum and minimum thermometers are used and properly exposed. The mean of the daily extremes is, as a rule, slightly too high, but it usually does not vary more than one-half of a degree from the true daily average. This combination is employed by the Weather Bureau to obtain the average daily temperature, and the data for the accompanying charts and diagrams were compiled by its use.[2]

A superficial analysis of some data indicated that the variation of temperature with altitude at the same general altitude differed with the watershed, as, for example, the eastern and western watersheds of the Allegheny Mountains in Pennsylvania. Therefore, in this analysis the country was divided into six districts as shown on the map, figure 1, as follows:

District No. 2—North Central United States (Mississippi Watershed).

District No. 3—Northern Rocky Mountains and Western Seaboard.

District No. 4—Southern Atlantic Seaboard.

District No. 5—South Central United States (Mississippi Valley).

District No. 6—Southern Rocky Mountains.

In order to simplify the analytical work, the border lines of the districts, in most instances, have followed the border lines of the several states included in each. While this makes for odd-shaped districts, a check on one district in which the northern and southern border lines were made to parallel the lines of latitude showed that the complexion of the results was not materially changed.

The mean variation of temperature with altitude for the entire United States for all years of record for 3,119 Weather Bureau stations, is shown in figure 2. The slope of this curve indicates a decrease in average temperature of approximately one degree for every 330-foot increase in altitude. This curve of temperature with altitude is not a straight line and the increment of elevation per degree of average temperature will vary. In a report from the United States Weather Bureau,[2] it is stated that the

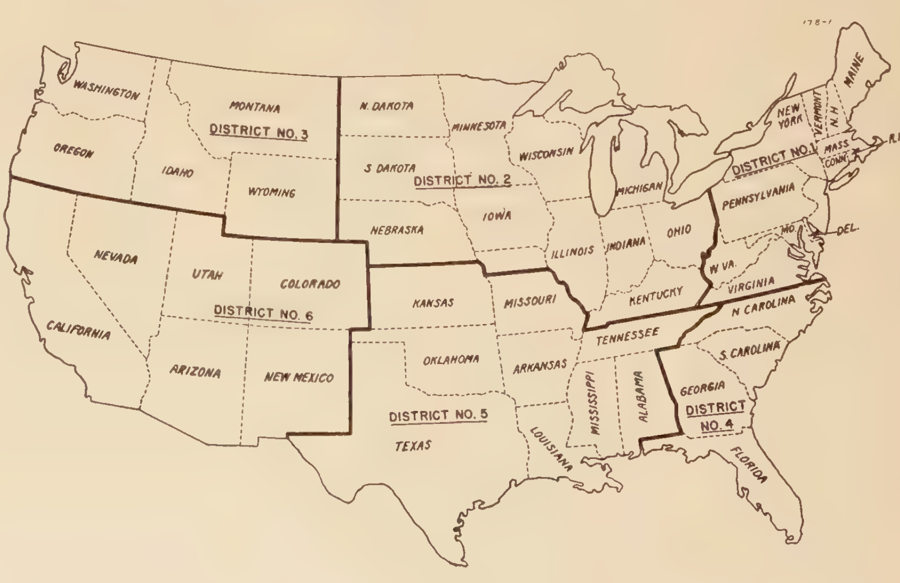


Figure 1. Subdivision of country into districts for temperature-altitude analysis

Paper 41-78, recommended by the AIEE committee on standards, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 19, 1940; made available for preprinting December 16, 1940.

H. W. TENNEY is manager of the engineering laboratories and standards department of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Penna.

The author acknowledges the able assistance of C. S. Hague, Jr., and R. C. Fowler in analyzing the vast amount of Weather Bureau data, which form the basis for the curves presented in this paper.

1. For all numbered references, see list at end of paper.

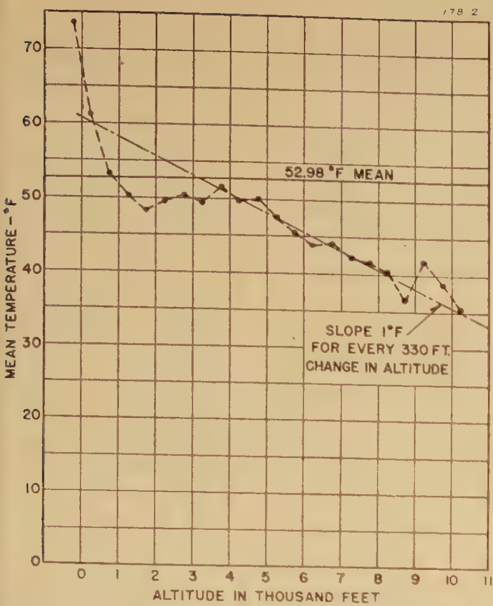


Figure 2. Variation of mean temperature with altitude for the entire United States

(Temperatures are mean for all years of record based on data from U. S. Weather Bureau reports)

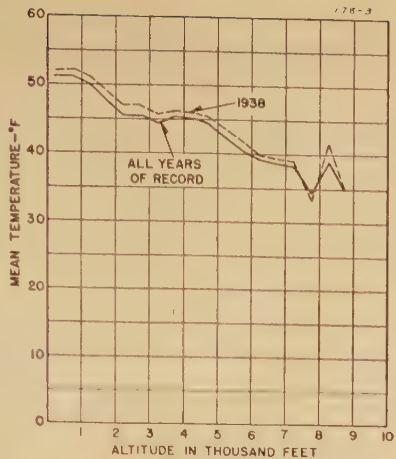


Figure 3. Comparison with altitude of mean temperatures for the year 1938 and mean temperatures for all years of record

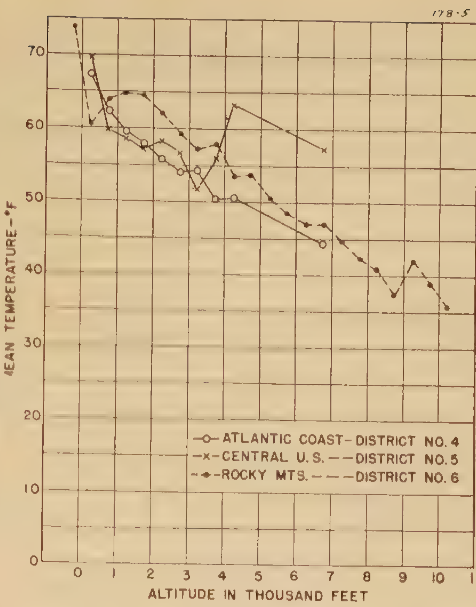


Figure 5. Variation of temperature with altitude for the southern districts of the United States

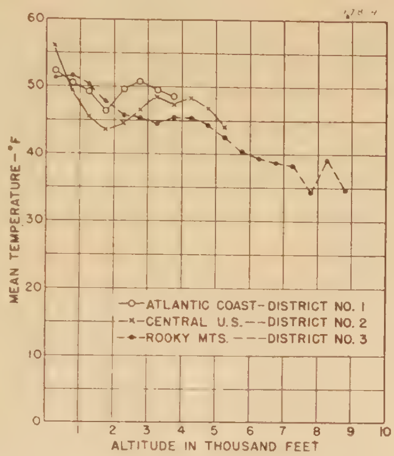


Figure 4. Variation of mean temperature with altitude for the northern districts of the United States

average decrease in temperature with increase in altitude in free air is about one degree for each 330 feet, but the rate varies with the season of the year and also is much affected by local conditions. It is more rapid in summer than in winter and is greatest during the warmer hours of the day. A study made of temperature variation with altitude made in England,[3,4] determined by sounding balloons, showed a decrease in temperature of one degree Fahrenheit for every 300-foot increase in altitude up to approximately seven miles, beyond which there is no further reduction in temperature.

The length of time records have been kept at the individual observation stations varies from 2 to 159 years. Through the use of mean temperatures for varying lengths of time the influence of periodic changes of temperature may be introduced. A method of extending short-term records has been suggested for the purpose of developing a satisfactory comparison between prevailing temperatures of two stations.[4] This may be done by comparing the mean temperature at the short-term station with the mean for a similar period of a similarly located long-term station and assuming that the same relationship would exist between the long-term means of the two stations. This procedure was not followed out in this paper, because it would multiply the analytical work tremendously and the increase of accuracy that might be expected would not warrant it. This is demonstrated in figure 3, which shows two curves of variation of temperature with altitude. One is the mean temperature for the year 1938 and the other is the mean temperature of all years of record. The year 1938 was a warm year and the annual mean temperatures for the entire country were above normal. However, in comparing the mean temperatures of one year with the mean temperatures for all years of record, it is seen that the curves are similar in shape and the difference between them is not great.

Figure 4 shows the variation of mean temperature for all years of record for the three northern districts numbers 1, 2, and 3, of the United States, and in figure 5 the same curves for the three southern districts numbers 4, 5, and 6 are shown. In order to interpret these clearly a brief description of how the data were worked up will be helpful. The mean temperatures for all years of record for all Weather Bureau stations were first calculated from the annual mean of 1938 and the deviation of this mean from the mean of all years of record.[1] It was then arbitrarily decided that the temperature data would be analyzed on the basis of 500-foot increments in change of altitude. The mean temperature of all stations located at altitudes between 0 and 500 feet, 501 and 1,000 feet, etc., were averaged and plotted halfway between the 0 and 500, 501 and 1,000, etc., ordinates on the curves. Analysis of the districts, using smaller increments for altitude, may influence the shape of the curve slightly, but will not seriously affect the general considerations involved.

Referring to figure 4, it is seen that the temperature decreases quite rapidly from 0–2,000 feet. There is then a reversal in the slope of the curve and the temperature increases gradually up to 3,000 or 3,500 feet. The mean temperature again falls off with increased altitude, but at a slower rate than in the first part of the curve. The curve of the Northern Rocky Mountain district seems to become erratic at the high altitudes. This is probably explained by the fact that there is only one Weather Bureau station in the ranges of altitude of 7,500–8,000 and 8,000–8,500 and only two in the range of 8,500 to 9,000. In ranges where only one or two stations are located unusual local conditions are not averaged out This is shown even more clearly in figure 5 in the curve for South Central United States for the ranges of altitude of 4,000–4,500 feet and 6,500–7,000 feet. These points are also for only one Weather Bureau station. The data for the point in the 4,000–4,500 range were taken at Alpine, Texas, and extend over a period of 16 years. Therefore, any extreme annual

Methods of System Control in a Large Interconnection

EARLE WILD
MEMBER AIEE

Synopsis: This paper describes the principles used in controlling the load in a large interconnected system. Automatic frequency controllers with time-error correction and tie-line controllers with frequency bias and time-error correction have been developed for co-ordinating the operations of interconnected systems of any size and geographical extent. Automatic control of two or more stations simultaneously within a group is described, and the relation of the auxiliary frequency controllers to the speed governors is also discussed.

Introduction

THE interconnection of many contiguous power systems into large co-ordinated groups of several million kilowatts has made imperative the development of control apparatus of great variety and refinement. The intended purpose of these interconnections required that economies of generation be maintained and that designated power flows be held steady. The geographical extent and the variety of relationships between the many properties made it necessary to use control equipment which would function in widely separated locations and with a minimum of direction. Increases in the size and number of large variable loads indicated the need for closer speed control. The final object of the control apparatus, therefore, was to maintain the most constant frequency and thus permit each local group to operate its individual system as local requirements dictate for maximum economy.

Paper 41-80, recommended by the AIEE committee on power generation, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 28, 1940; made available for preprinting December 16, 1940.

EARLE WILD is load dispatcher for the Commonwealth Edison Company, Chicago, Ill.

Basic System of Control

The original system of control consisted in giving one central group responsibility for the frequency control. All other groups starting from this point were interconnected through one or more tie lines which were held at definite scheduled loads. These other groups thus were varying their own generation locally, to meet their own load requirements. Theoretically, the frequency-control stations would only be following the variations in the load of the central group. Automatic frequency controllers and automatic tie-line controllers were used for this purpose.

Two objections arose to this simple plan. When two, three, or sometimes more of the tie lines departed from schedule in the same direction, the frequency-control station was unable to restore the frequency without an excessive load change. The other objection came from the continual variations in frequency causing the tie-line loads to vary. It was not only difficult to maintain these tie-line loads at scheduled value, but a large part of the regulation was being done in opposition to the frequency correction of the central group. Thus the original simple system of control did not function as well as intended.

Tie Line Biased by Frequency

These difficulties led to the development of the tie-line biased-by-frequency method of automatic control, which is

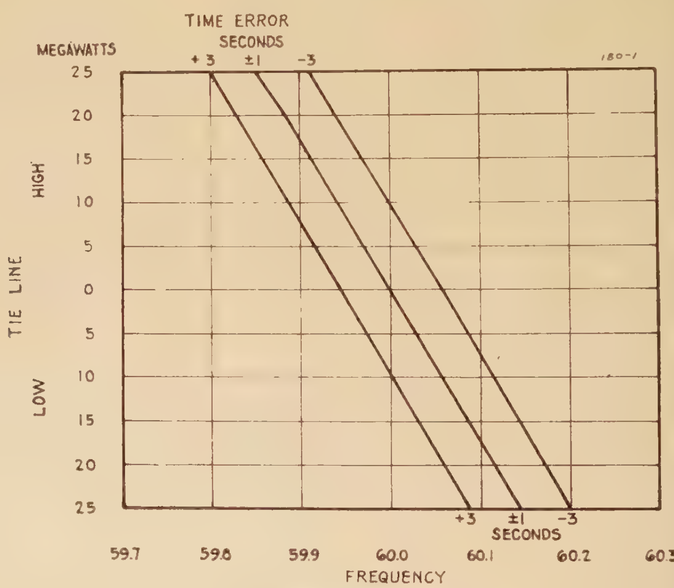


Figure 1. Characteristic curves of a tie-line controller

Shows tie-line load departures from normal, for corresponding frequency and time-error deviations

condition should be fairly well averaged out. The displacement can only be explained by unusual local conditions. On the other hand, the point in the 6,500–7,000-foot range is for the Weather Bureau Station at Mount Locke, where the period of record is only four years. Here a year of unusual temperature conditions might have affected the mean temperature some but probably not sufficiently to bring this point within the more or less expected trend of the curve.

Examination of figure 5 shows changes in slope at different points along the three curves, but these do not appear in the same range of altitudes as was the case with the three northern districts. As would be expected, the mean temperatures at the lower altitudes are higher than for similar altitudes in the northern districts. However, the curves for the northern and southern districts approach each other at the higher altitudes.

As seen from figure 2 the retardation and inversion of the temperature-lapse rate supports the general practice of making no correction for ratings for altitudes up to 3,300 feet (1,000 meters). Data are presented here from which a basic study may be made to determine the limits at which standard apparatus may be used at higher altitudes.

References

1. Climatological Data of the United States for 1938 from the United States Weather Bureau, Department of Commerce, Washington, D. C.

2. ATLAS OF AMERICAN AGRICULTURE, Part 2, Climate, Section B, Temperature, Sunshine and Wind, Joseph B. Kincer, senior meteorologist, United States Weather Bureau, Department of Commerce Washington, D. C.

3. SIR JOHN MOORE'S METEOROLOGY (book).

4. ELEMENTS OF HYDROLOGY (book), A. F. Meyer.

being used extensively in large interconnections. With it, the fundamental plan of regional control of loads is continued, but instead of holding tie-line loads at constant value, they are permitted to deviate from schedule whenever the frequency varies and in a direction to relieve the burden of the frequency-controlling center. The amount the tie-line load is varied, commonly known as *bias*, is a function of the frequency effect on load and the action of the speed governors of the turbines. This relationship will be described in a later section.

This bias principle permits tie-line loads to be varied in a relieving direction and be restored with a minimum change in generation in each group. It also assures the frequency-regulating center that several tie lines will be biased correctly for each one causing a frequency departure from normal. Thus any number of groups may be interconnected under this plan without increasing the burden of the central group.

The performance on several of these tie lines has been checked by means of counters, which register the deviations from normal. These show that most groups hold to scheduled tie-line loads about 70 per cent of the time, cause frequency deviations about 10 per cent of the time, and vary in a direction to relieve the frequency deviations 20 per cent of the time. Actually, each group on bias is assisting, in direction at least, twice as much as it is contributing to frequency deviations.

Frequency Effect on Load

Before the correct amount of bias could be determined for any system it was necessary to know the effect of frequency changes on the load. Studies were made in the Chicago system to determine the amount of load change for a given frequency change. It was found, as a very general rule, that one-tenth-cycle frequency departure resulted in approximately a one per cent change in system load. This figure is somewhat less than has been observed on some large interconnections, but has been checked many times since the staged tests were made, whenever important intersystem tie lines opened automatically under heavy load and there were sudden frequency changes. This figure takes into account the average response of a composite group of governors on the turbines affected, as they are found in normal service and without unusual attention being given to increasing their sensitivity or to block them.

This figure also includes some effect of voltage changes. Whenever the frequency departs from normal there is a change in voltage, due to change in the speed of the shaft-driven exciters on the main turbines. A test in one large load zone, which is mostly industrial in character, shows that whenever the voltage drops one per cent there is a $1^1/_2$ per cent drop in customer load. However, when the frequency drops there is not a general drop in voltage proportional to the drop in speed, as the automatic voltage regulators provide correction for at least 50 per cent of the load. Probably the largest effect of minor frequency changes comes both from a change in speed in the industrial motor load and the action of the more sensitive speed governors.

Tie-Line Bias Setting

The tie-line bias setting used is the one which will permit the tie-line load to change an amount equal to the group-load change for any given frequency deviation. As the frequency rises the load increases, but the generation remains constant except for the small decrease caused by the speed governors. The tie line supplies the difference and thus tends to oppose the frequency rise. When the frequency is restored to normal the tie-line load is returned to schedule without adjusting the generation. Thus whenever the frequency varies one-tenth cycle, the tie-line load is changed an amount equal to one per cent of the total generated load. This bias is extended proportionally for other departures from the normal of 60 cycles.

Time-Error Bias

There are times, however, after the frequency has departed from normal for a considerable period, when it is necessary to arbitrarily offset the frequency in the opposite direction in order to correct an integrated frequency or time error. If a great many of the tie lines in an interconnection are being operated on the tie-line bias principle, it becomes very difficult for the centrally-located frequency-control station to offset the frequency manually. It was desirable, therefore, to add time-error bias to each of the frequency-biased tie lines. Whenever the time departs from normal a time-error indicator, therefore, similarly causes a departure in tie line in such a direction as to offset the frequency and correct the time error.

Figure 1 is a chart of the relation of tie-line load to frequency and electric time error in a controller. All three of these factors must be satisfied, or the controller will change the system load until the tie-line load reaches a balance point. Figure 2 shows the changes in tie-line load as the frequency and time-error deviate from normal on a large group.

Description of Controllers

The equipment used in the control consists of the following apparatus:

1. Frequency controller with an electric time-error correction.
2. Tie-line controller.
3. Tie-line controller biased by frequency.
4. Tie-line controller biased by frequency and with electric time-error correction.
5. Cascading settings of tie-line controllers when used in series.
6. Devices for controlling the load on two turbines in separate stations.

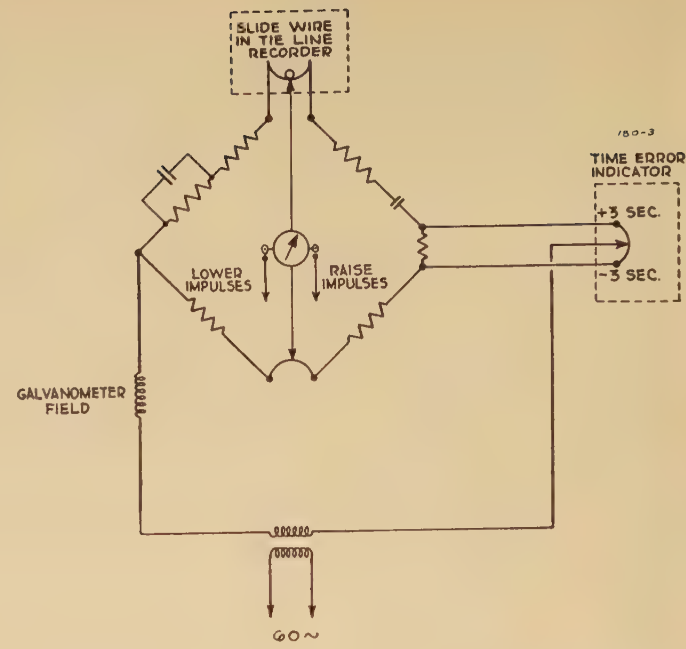
The tie-line controller biased by frequency and with electric time-error correction, and the frequency controller with electric time-error correction will be described. Figure 3 shows a diagram of the electrical circuit of a typical tie-line controller, which has both frequency bias and time-error correction. The apparatus, as commonly used for this purpose, consists of a frequency bridge which is tuned for 60 cycles. One corner of the bridge has been opened and extended to a slide wire mounted in the recording tie-line meter. The zero or center point of this slide wire has a front "setter" and is placed at the scheduled tie-line point, wherever that may be from hour to hour. The movable contact of this slide wire is operated by the tie-line recorder carriage. Whenever the tie line is at the scheduled point, the contact is in the center of the slide wire and the frequency bridge remains balanced. If the tie line is displaced to one side or the other of the zero point, more resistance is inserted in one leg of the frequency bridge than the other, calling for a change in frequency in order to restore the balance of the galvanometer circuit or the correction of the tie-line load. Similarly, a second corner of the frequency bridge has been opened and extended to a slide wire in a time-error indicator. This time-error indicator consists of two electric motors, one driven by the system frequency and the other driven by the exact frequency of 60 cycles obtained from a crystal oscillator time standard. The speed of these two motors is compared through differential gearing, and any resulting displacement operates the pointer on the slide wire of the time-error indicator to change appropriately the balance point on the frequency bridge.

In order to regulate a system within plus or minus one second over widely scattered controllers requires that highly accurate time standards be provided. Some of the larger cities have sources of astronomical time, but these are not generally available over a wide interconnection. It has been agreed, in this interconnection, to use the primary frequency standard of the crystal oscillator type as a source of true time. These have an error of one part in two million and may be readily compared with observatory time as received from Arlington. Even assuming an error in setting these oscillators at widely scattered points, it will not be difficult to keep the time-error indicators within a quarter of a second of each other. The amount of tie-line departure that might be introduced by an error of a quarter of a second in the time standard would, at the most, be only one or two megawatts in any group.

The apparatus in the frequency-controlling centers is similar to the tie-line controlling apparatus described above, except that there is no tie-line slide wire. The bridge is continuously tuned for 60 cycles, except when the time-error indicator is displaced from its center point.

The galvanometer is a Leeds and Northrup contact-making type, in which there are wiping cams which make contact with the "raise" or "lower" circuits once every two seconds. The duration of these contacts is proportional to the amount the frequency has deviated from the calibration value of the frequency bridge.

Figure 3. Circuit diagram of a tie-line controller, with frequency bias and time-error correction



Rate of Load Response

The galvanometer circuit is unbalanced any time one of the three characteristics is varied from the normal value. If two of the characteristics are abnormal, the galvanometer is still further unbalanced unless these two are in opposition.

Comparison of these counterinfluences in the frequency bridge is very important. For example, if the tie line is off schedule and the frequency has not departed from normal, indicating that the load in some other group of companies is off schedule in the opposite direction, the controller sends out very short corrective impulses and it takes considerable time for this tie-line error to be corrected. Similarly, the other zone, whose generation is displaced from the correct value in the opposite direction, would be making a very slow correction and the load of the frequency-controlling center would not need to be disturbed. If, on the other hand, were the tie line to be off schedule in the same direction as the frequency, indicating that this group of companies is producing the frequency departure, the controller would send out very long impulses and cause the generation to change very rapidly at the point which was most responsible for the frequency departure.

The unbalancing of the bridge by time error is a much more gradual influence and requires, likewise, a much longer period for the time correction.

The controllers in the large group have been set to give a maximum correction to tie-line load of 20 megawatts in 30 seconds. The frequency-controller group has about one-half this rate of response, and the smaller groups are decreased to one megawatt a minute.

Cascading of Controllers

Several controllers may be installed in series along an extended transmission link, as shown in figure 4. The one most remote from the frequency-control center is given a bias setting proportional to the

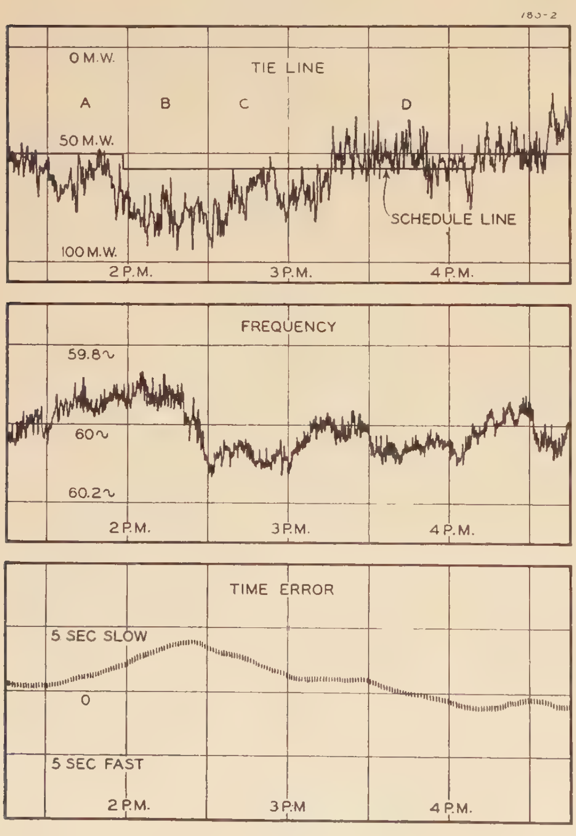


Figure 2. A tie-line load curve showing variations from schedule, effected by frequency and time-error biases

The tie-line load is (*A*) high with low frequency, (*B*) increasing with slow time error, (*C*) decreasing with high frequency but continued time error, (*D*) low with high frequency

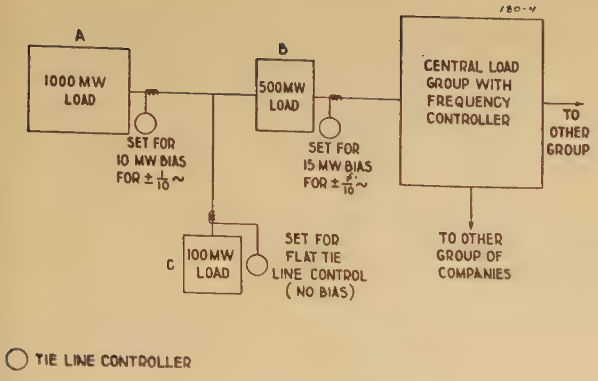


Figure 4. Cascaded settings of three tie-line controllers on a transmission system

Bias setting of group *B* includes bias of group *A*, but does not include group *C*, a small system operating on flat tie-line control

size of its system. The next controller toward the frequency-controlling center is given a setting which includes its own proportional bias and the bias of the controller in back of it. If there are controllers in smaller companies which are on flat tie-line settings or which are held manually at a constant value, these, of course, are not taken into account in determining the bias setting. The controller which is nearest to the frequency-controlling center and having the highest bias may actually be operating in one of the smaller companies or one of the smaller generating stations. If the controller in the more remote company should fail to effect its tie-line departure, the controller more centrally located would then be called on for a contribution out of proportion to the size of the latter company. This is prevented in two ways: (1) By a suitable load-limiting band on the generators which restrict the departure to a proper value, and (2) by limiting the rate of response of the smaller controller so that the larger company will have sufficient time in which to make its correction before the smaller company has made an extended departure from its normal generation.

In one large interconnected system there are now 60 companies operating in parallel. These have generally adopted this principle of frequency and tie-line control. There are 17 of these controllers operating in parallel, 2 of them regulating the frequency only, and the other 15 on one or another form of tie-line control. The smaller companies are generally on flat tie-line control unless they are in series with a larger group which is on bias. One has installed time-error correction, and several others are now providing time-error correction equipment. With this method of control all local problems of generation are handled locally. Responsibility for frequency departures or inadequate generation is indicated at its source and corrected. The physical distance between companies or groups of companies is not a limitation, and new groups may be added to the interconnection and perform satisfactorily by adding a new controller without requiring changes in any of the existing facilities.

New interchange contracts which are made locally between any groups of companies do not call for changes in the apparatus, as it is adaptable to almost any power-flow requirements. The only precaution necessary is that the frequency bridges must be reasonably accurately tuned for 60 cycles. Where time standards are provided this is very simply checked, and where there are no standards, other apparatus, such as tuning forks, can be used, which will permit checking the frequency bridge accurately enough for load-control purposes.

Simultaneous Automatic Control of Two Stations

Once a company or group of companies have installed a controller, the problem arises as to the method to be used in utilizing the controlling impulses. The load and the number of generating stations have frequently grown to a point where it is not practical to assign the regulating responsibility to one station. This has been overcome in the Chicago area by the installation of one controller, which is sending its correcting impulses to two generating stations simultaneously. This appears to be the best arrangement in any company or group of companies which are operating under a pooling arrangement, and the control of the load on the local transmission system is not necessary.

After the controlling impulses are directed to two stations, it is desirable that the turbine selected for the automatic control in each station respond in similar amounts to the identical impulses. These turbines may be of different size and have entirely different governor characteristics. Two devices have been used for introducing these impulses into the governors of the respective turbines. One of these consists of a rheostat which operates a torque motor attached to the pilot cylinder of the governor, and makes a small and controlled load change. The two rheostats may be easily timed to travel at the same rate in the two stations, and by control of the necessary torque they can be made to make similar load changes, except at valve-opening points. These valve-opening points are traversed manually. This device, acting on the pilot valve, is not only faster in response than the synchronizing motor, but it avoids any inertia or loose play which is present in governor linkage. The rheostat also acts as its own load-limiting device.

The other apparatus which has been developed consists of an instantaneous wattmeter of the Kelvin balance or electronic type, in which the small driving motor in the meter is used to drive the carriage of the meter from the impulses of the controller. The impulses are also sent to the synchronizing motor, and if the turbine makes a larger load change than required for the length of impulses being used, the wattmeter becomes unbalanced and interrupts any subsequent impulses

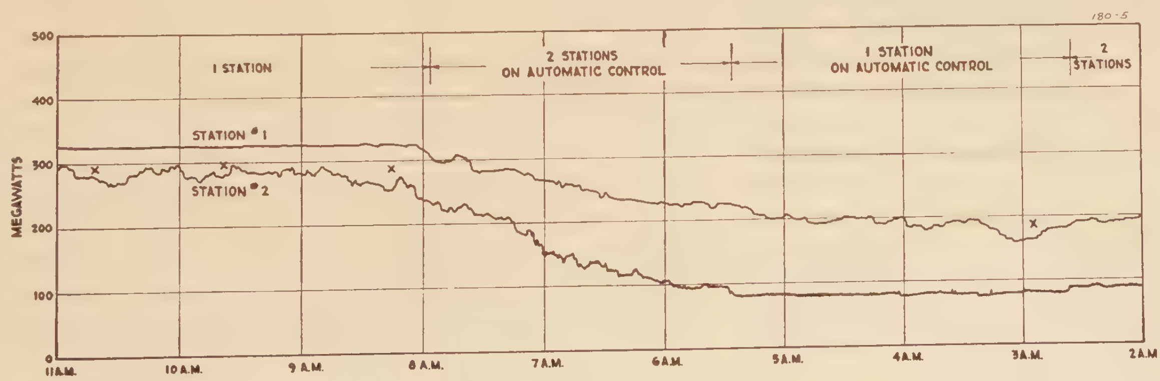


Figure 5. Load curves of two stations equipped for simultaneous automatic control

Amount of load variations at (*X*) increases sharply when only one station is on automatic regulation

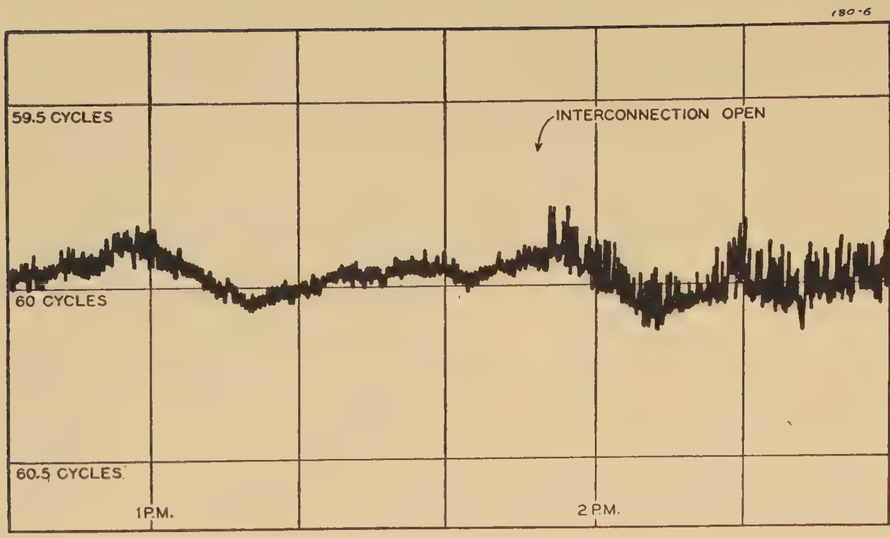


Figure 6. Frequency curve of a large system, showing effect of interconnections on width of frequency variations

to the turbine. The speed of the driving motors in the two wattmeters can similarly be timed together.

Need for More Automatic Control of Stations

In any station which has automatic load control, the variation in its load can be analyzed to come from two sources: One, the variations in the load of the system as it changes from minute to minute, and the other the irregularities in generation of the nonautomatic stations. These latter variations are caused largely by the inability of these stations to follow adequately the system-load changes. Frequently it has been found that some of the largest burden on the automatically-controlled station comes from the simultaneous delayed action on two or three other stations within the same group.

In the Chicago system an attempt was made many years ago to assist all stations in following the load trend by having a system totalizer in every operating gallery, which would indicate the total system load at all times. Each operator was then given a schedule which indicated the portion of the system total load assigned to that station. Although this method has proved quite workable, no operator is able to follow manually the trend as fast as the automatic station does, and so after each large load change it is found that the regulating station has to make a counterchange of load as the other stations follow manually.

In a system of, let us say, five stations, one may be a base-load station, another the automatically-controlled station, and the other three following the trend either manually, as observed on a totalizing meter, or under load dispatcher's orders. If these latter three, or at least the one or two of them making the largest load variations, could make their change in load before the full-load change of the automatic station has been completed, the burden on the automatic station would be very sharply reduced.

The experience in Chicago with two stations operating simultaneously (figure 5) indicates that the burden on either one is less than half what it would be if only one were on automatic control. This indication has proved so definite that steps are now being taken to extend the automatic control to practically all the major generating stations. The so-called base-load stations during the minimum hours become the variable-load stations on the system, and at these hours take over the automatic regulation.

Relation of Controllers to Governors

The function of the auxiliary speed device or frequency controller, as it is commonly called, does not supersede that of the speed governor. The speed governor must continue to maintain instantaneous frequency, but in maintaining this frequency it distributes the load in a manner that is often not desired. The controller, on the other hand, is relatively slow in its action, but it does give droop correction, which the governor cannot do, and it can easily be made to properly allocate the load in any proportions desired. The importance of the governor seems to vary inversely with the size of the electrical system.

Figure 6 shows the frequency variation in a large system while it was part of a much larger interconnection and also while it was being operated isolated. Certainly it is apparent that the smaller systems, especially if supplying variable loads, must have the turbines equipped with the best governors available. In the large interconnections, on the other hand, there is an enormous inertia effect available, which holds the system speed within a very narrow band. This has led to the belief in some quarters that the governors should not be too sensitive and may even have a small dead band.

The load-control problem is generally rather easily handled in a small isolated system. The large interconnection-load control is much more difficult. Although the instantaneous frequency varies but little from minute to minute, it does drift over the longer period of hours or more, over a much wider band than is found in the small systems. This is a load-control problem, which must be handled by the controllers or by supplementary manual action.

The manufacturers have proposed that governors be built with a sensitivity of 0.04 per cent and a per cent regulation up to two per cent. These are undoubtedly desirable on the smaller systems, but on the large interconnections governors with a sensitivity of 0.08 per cent and from four per cent to six per cent regulation would be satisfactory. Where flat tie-line regulation is used, the action of too responsive governors is contrary to the action called for by the controllers. With the tie-line bias principle, however, more responsive governor action could easily be accommodated by increasing the amount of bias setting. The problem of modernizing enough governors in a large interconnection, where they may run up to 1,000 in number, so that a few will not be carrying a large portion of the regulation, is very difficult, and also the benefits to be derived from such a program are probably quite limited.

Conclusions

1. A centrally located frequency control with automatic tie-line controllers maintaining the proper loads locally, has proved to be a practical method of holding steady the frequency in large interconnections, regardless of size or numbers of interconnections.

2. The tie-line biased-by-frequency principle relieves the regulating burden on both the frequency control and the tie-line regulation stations.

3. Several of the variable-load stations in any group should be sharing the automatic regulation.

4. Adequate governors are necessary, but it appears that the sensitivity and per cent regulation of these governors may vary inversely with the size of the systems and the nature of the load.

Modern Relaying for A-C Secondary Network Systems

D. L. BEEMAN
ASSOCIATE AIEE

Synopsis: This paper outlines the application of a new three-phase, single-element induction cylinder network master relay which uses line-to-line connected potential coils. Previous network master relays were three-phase, three-element and employed line-to-neutral connected potential coils.

The new relay with line-to-line connected potential coils produces far greater tripping torque during unbalanced primary feeder faults than the older relays with line-to-neutral connected potential coils. Examples are given to show the advantage of the new relay.

Modern relays have materially improved tripping characteristics which extend the range of highly leading and lagging currents over which the relays will operate selectively at normal balanced three-phase voltages.

The mechanical improvements of the network relays are discussed.

Introduction

DURING the past decade there have been many improvements in relays for a-c secondary network systems. There have been no basic changes in the functions performed by these relays. However, the introduction of a new single-element, three-phase induction cylinder relay with line-to-line connected potential coils and improved electrical and mechanical features, represents a basic change in the design and performance of these relays. The major improvements have been made in tripping performance and mechanical construction.

In the conventional *a-c secondary network system,*[1] figure 1, a secondary grid is fed by a number of network transformers which are supplied from a substation through two or more high-voltage feeders. The function of the network protector, located on the secondary of each transformer, is to disconnect automatically all transformers, on a faulty feeder, from the secondary grid. Hence, the grid will remain energized and continue to supply all loads from the healthy primary feeders. After the faulty feeder has been restored to normal and re-energized, it is the second function of the network protector to automatically reconnect the transformers on that feeder to the secondary grid.

The tripping of the network protectors is performed by a three-phase power directional relay, commonly called the "master relay," and the reclosing is performed by the same three-phase relay in conjunction with a single-phase "phasing relay."

Secondary network systems are now being more generally applied to areas which are relatively *lightly loaded.*[2] Installations in these areas are characterized by wide spacing of transformers, and relatively high secondary grid impedance, and consequently *lower fault voltages and currents* during primary feeder faults than are generally encountered in heavy-density systems which are more closely coupled. Hence, it is more difficult for the master relay to operate to trip the network protector during primary feeder faults in light-density than in heavy-density secondary network systems.

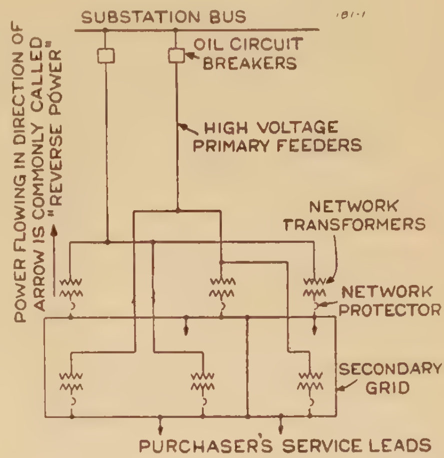


Figure 1. Schematic diagram of a-c secondary network system

Figure 2. Three types of three-phase network master relays

Left—Three-element induction disk relay

Center—Three-element induction cylinder relay

Right—Single-element induction cylinder relay

New Single-Element Master Relay

The new single-element three-phase master relay, figure 2 (right) overcomes this difficulty first because on three-phase primary feeder faults it produces more torque in proportion to the weight of the moving element than does any other master relay. Hence, there is a greater margin between the total torque and the friction torque which increases the useful torque available for operating the relay.

Further improvement is obtained by using *line-to-line* (*L-L*) *instead of line-to-neutral* (*L-N*) *potential coil connections.* This parallels transmission line relay practice where most directional relays use *L-L* connected potential coils. A

Paper 41-81, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 26, 1940; made available for preprinting December 16, 1940.

D. L. BEEMAN is application engineer for the General Electric Company, Schenectady, N. Y.

Acknowledgment is gratefully made to L. F. Kennedy for his assistance in preparing this paper and to V. Stewart for obtaining certain data used.

1. For all numbered references, see list at end of paper.

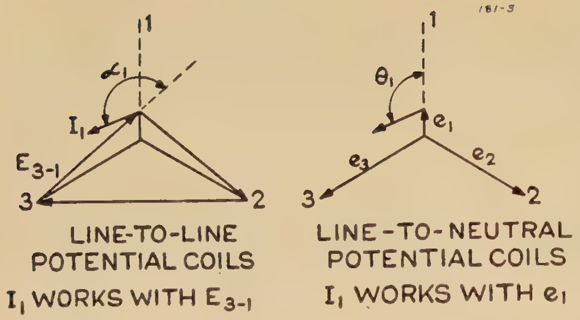
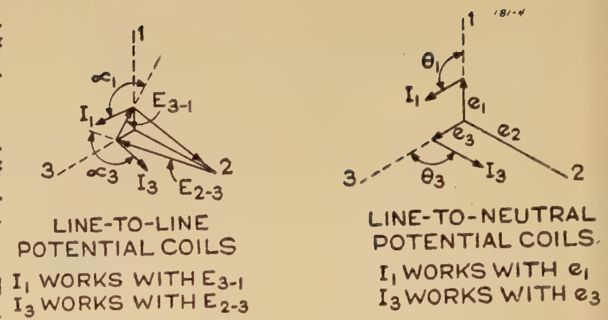
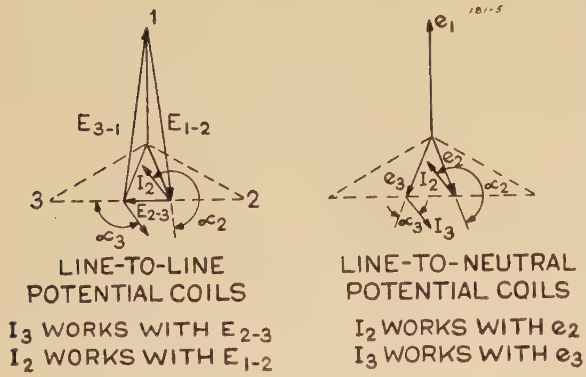


Figure 3 (left). Vector diagram of line-to-ground primary feeder fault

Figure 4 (right). Vector diagram of double line-to-ground primary feeder fault

Both wye-connected high-voltage windings in network transformer

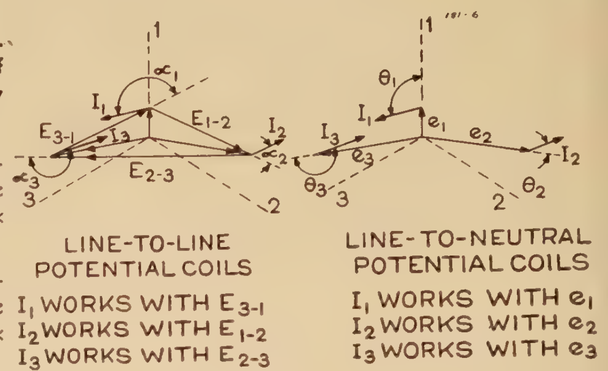




Figures 5 and 6. Vector diagrams of line-to-line primary feeder faults

(Left). Wye-connected high-voltage winding in network transformer

(Right). Delta-connected high-voltage winding in network transformer



given relay will produce considerably *greater torque under unbalanced primary feeder fault* conditions with *L-L* than with *L-N* connected potential coils. The torque produced during three-phase primary feeder faults or under balanced three-phase conditions is the same for a given relay whether *L-L* or *L-N* potential coil connections are used.

The greater ratio of torque to weight of moving element makes the single-element relay attractive for use in heavy-density secondary network systems as well as in light-density secondary network systems. The *L-L* potential coil connections are advantageous for master relays used in heavy-density networks because there is always some reduction in voltage when unbalanced primary feeder faults occur. Therefore, the new single-element master relay, although originally developed for light-density network systems, is now applied to heavy-duty network protectors for heavy-density networks. The following discussion applies to network systems in general.

Relay Performance During Unbalanced Primary Feeder Faults

The advantage of the three-phase single-element relay with *L-L* connected potential coils can be readily seen by referring to figure 3 and table I. In table I comparisons are made at three different voltages. Figure 3 is a vector diagram of the voltages existing at the relay for *a line-to-ground primary feeder fault on a wye-connected transformer.* There is fault current I_1 in only one phase of the system, and hence only one phase of the master relay. With the older relays, with *L-N* connected potential coils, this current I_1 reacts with line-to-neutral voltage e_1 which is very small and the power factor is very low. With the new three-phase single-element relay with *L-L* connected potential coils, the torque is considerably greater because the same fault current I_1 reacts with line-to-line voltage E_{3-1} which is far greater in proportion to normal than e_1. Furthermore, the fault current is closer to the maximum torque position of the *L-L* relay, which further increases its torque.

Other possible unbalanced primary feeder faults are: (1) double line-to-ground, and (2) line-to-line faults. The actual torques for two similar relays with *L-N* and *L-L* connected potential coils are compared in table II.

The vector diagrams in figures 4, 5, and 6 show pictorially the relation between the fault voltages and currents in the two relays employing *L-L* or *L-N* potential connections.

The increased torque of the new relay during unbalanced primary feeder faults provides more positive operation and also increases the speed of operation of the relays, table III.

Hence, it permits more latitude in selection of network-protector fuses without the probability of a fuse blowing on unbalanced primary feeder faults before the master relay trips the network protector.

The greater torque of this relay has proved particularly advantageous where higher reverse power settings are required to prevent "pumping" of the network protector during normal operation. These higher settings may actually prevent a relay with *L-N* potential coils from tripping during certain unbalanced primary feeder faults. The greater torque produced by the single-element relay with *L-L* connected potential coils permits greater reverse power settings without the relay failing to trip on unbalanced primary feeder faults.[3]

Singe-Phase Switching of Primary Feeders

In some installations light-density networks are fed from overhead 4-kv wye-connected primary feeders with *single-phase switching* at the source or single-phase fuses between the source and the network transformers. A single phase-to-ground primary feeder fault may open only the faulty phase at the substation or at the fuse. Then there is reverse power on one phase being fed from the secondary grid through the transformer. This produces a tripping torque on one phase of the master relay. The other two phases may be supplying load to the network grid and this would produce a non-tripping torque in the other two phases of the master relay. If the relay is to trip the protector the torque produced by the fault current and voltage in one phase must overcome the torque produced

Table I. Comparison of Relays for Line-to-Ground Fault, Figure 3

Fault Current (I_1)* (Per Cent)	Potential Coil Voltage Which Operates With (I_1)*	Angle Between Fault Current and Maximum Torque Angle of Relay (Degrees)	Per Cent of Normal Torque** L-L Relay	Per Cent of Normal Torque** L-N Relay	Ratio of Relay Torque L-L to L-N
200	10% e_1	75		1.7	15.30
200	58% E_{3-1}	47	26		
500	25% e_1	75		11	6.1
500	71% E_{3-1}	55	67		
1,400	70% e_1	75		81	1.70
1,400	85% E_{3-1}	51	139		

*Fault current and potential coil voltage are in per cent of rated current and voltage of associated network transformer.

**Normal torque is the torque produced by the relay with all three phases energized with rated voltage and rated current at the angle of maximum torque.

Table II. Comparison of Master Relays for Various Types of Unbalanced Primary Feeder Faults, Figures 4, 5, and 6

Basis: Fault Voltage Equals 25 Per Cent of Normal. Power Factor of Fault Current 75 Degrees Lagging

Type of Fault	Transformer Primary Connection	Per Cent of Normal Torque L-L Relay	Per Cent of Normal Torque L-N Relay	Ratio of L-L to L-N Relay Torques
Double line-to-ground	Wye	$15.1\frac{I}{I_n}$*	$4.2\frac{I}{I_n}$	3.6
Line-to-line	Wye	$24.8\frac{I}{I_n}$	$3.7\frac{I}{I_n}$	6.7
Line-to-line	Delta	$21.4\frac{I}{I_n}$	$3.2\frac{I}{I_n}$	6.7

* $\frac{I}{I_n}$ = Ratio fault current to rated current of network relay.

Table III. Comparative Operating Times of Similar Relays on Single Phase-to-Ground Primary Feeder Faults, Figure 3, With L-L and L-N Connected Potential Coils

Fault Voltage 25 Per Cent Normal and Power Factor of Fault Current 75 Degrees

Fault Current In Per Cent of Normal	Operating Time in Seconds L-L Relay	Operating Time in Seconds L-N Relay
500	0.16	0.9

by the load current in the other two phases. The increased tripping torque of the single-element relay with *L-L* potential coil connections will be beneficial in these cases. Single-phase switching on primary feeders to secondary networks *is to be avoided wherever possible.*

Relay Connection

The basic differences in *L-L* and *L-N* potential coil connections are shown in figure 7. In this figure the *L-L* connections are shown to involve three potentials for the sake of simplicity. The actual connections of the new three-phase single-element master relay[4] are shown in figure 8. This relay uses two sets of potential coils in open delta.

Improved Tripping Characteristics

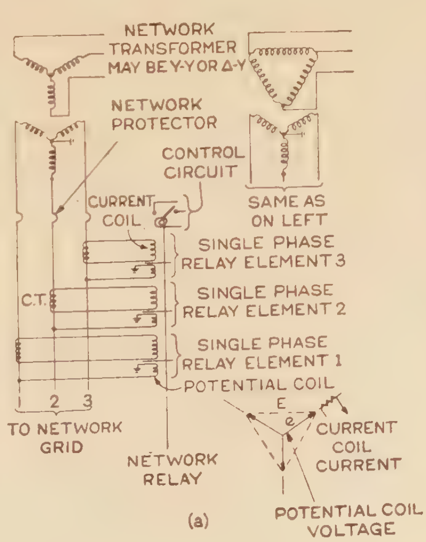
In addition to tripping on primary feeder faults as outlined above, network master relays must trip on very low values of reverse power flow (i.e., power flow from the grid to the network) such as transformer-core loss and cable-charging current, to enable clearing a primary feeder by merely opening the station breaker.

Since the relay must function on *very small power reversals* involving very highly leading cable charging current I_c and lagging transformer exciting current I_m, the ideal tripping characteristic would be that of a true wattmeter or curve *a-a′*, figure 9.

Practically, it is not possible to build a relay which has a truly wattmeteric characteristic because of the saturation of the iron used in the magnetic structures of the relay and the current transformers. The effect of saturation is to produce a characteristic like that of *c-c′*, figure 9. Currents through the protector represented by vectors terminating to the left of the characteristic will cause the master relay to trip the protector. Current vectors terminating to the right will not cause the master relay to trip the protector.

Improvements in the *quality of iron* available and refinements of the design of the *magnetic structures* of the relay have resulted in tripping characteristic *b-b′* (figure 9) for the modern induction cylinder single-element and three-element, three-phase master relays as compared with characteristic *c-c′* for early types of induction disk master relays.

The newer induction cylinder master relays with straighter characteristics enable more universal application as they permit selective operation with larger highly leading and lagging currents. The characteristics of earlier induction disk master relays were so bent that it would



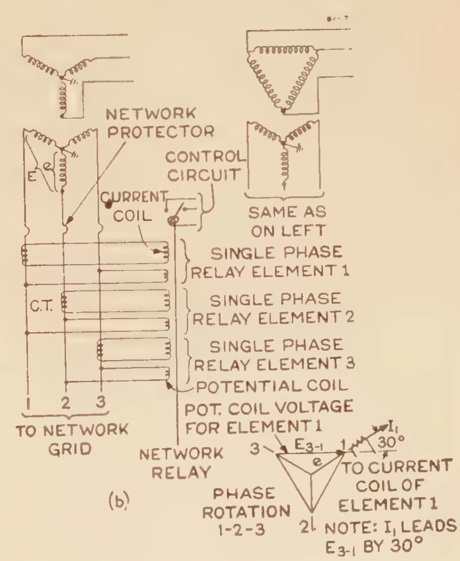


Figure 7. Schematic diagram of network master relay connections

(*a*)—Line-to-neutral connected potential coils

(*b*)—Line-to-line connected potential coils

Table IV. Comparison of Mechanical and Electrical Characteristics of Two Types of Older Three-Phase, Three-Element Master Relays and the New Single-Element, Three-Phase Master Relay

Type of Relay	Watts Input (Per Cent)	Torque Per Watt (Per Cent)	Ratio Torque to Weight of Moving Element (Per Cent)	Volume (Per Cent)
Three-phase, three-element induction disk relay (old)	100	100	100	100
Three-phase, three-element induction cylinder relay (old)	45	320	209	42
Three-phase single-element induction cylinder relay (new)	26	465	231	33

not be to the right of both I_c and I_m. Hence, it was necessary to adjust the characteristics of many of these relays to meet varying conditions and to restrict their application to locations where cable-charging currents were negligible.

Mechanical Improvements

The mechanical improvements of network relays can be seen in figure 2 and table IV where the principal characteristics were given.

The induction disk master relays, figure 2 (left), were relatively inefficient and occupied considerable volume. To permit a reduction in the size of protectors, it was desirable to reduce the size of these relays. This and the desire to improve the relay performance led to the development of the three-phase three-element induction cylinder relay shown in figure 2 (center). Electrically, this relay was the same as the induction disk type, i.e., it had three independent single-phase elements all on a common shaft and had L-N connected potential coils. The new single-element relay is a further improvement of the induction cylinder design in that all three phases are combined in one element with only one rotor.

Network relay adjustments have been simplified in that individual phase adjustments are not required. *Drag magnets* which were a source of maintenance on the older relays have been eliminated. Contacts have been developed that will withstand several thousands of operations without maintenance.

The above-mentioned refinements have been made mainly to *reduce maintenance* and to enable *longer time between inspection periods*. Maintenance is a particularly important factor in network relays because they are mounted in inaccessible locations.

Network relays operate at extremely low torques when tripping on transformer exciting current. Hence, friction plays an important part in the performance of these relays. The single-element master relay has a much lighter moving element; hence, the *friction force is lower*, and consequently operation is more positive. Induction cylinder relays have balanced magnetic circuits and are inherently free from vertical vibration. Hence the major source of bearing wear has been eliminated.

Modern network relays operate at a *lower temperature rise*, i.e., about 40 degrees centigrade rise over ambient around relay, to allow for higher ambients encountered inside higher capacity submersible network protectors now being built, without unduly shortening the life of the relay coils.

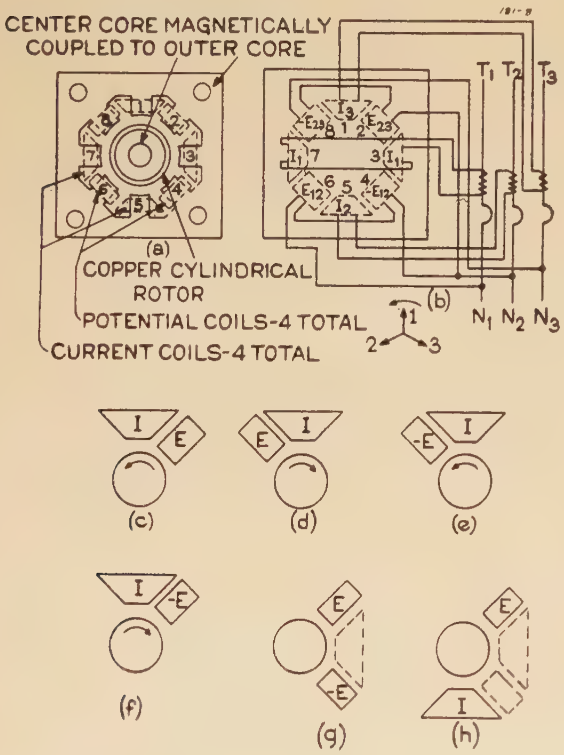


Figure 8. Schematic connections of single-element three-phase master relay

Summary

A new three-phase, single-element induction cylinder relay has been introduced which, although functionally the same as previous relays in so far as network-protector control is concerned, has:

1. Line-to-line connected potential coils instead of line-to-neutral connected potential coils which provides a far greater tripping torque during unbalanced primary feeder faults.

2. This is particularly advantageous in light-density network systems where fault currents and voltages are lower than in heavy-density systems which are more closely coupled. The line-to-line connected potential coils offer advantages in heavy-density systems too.

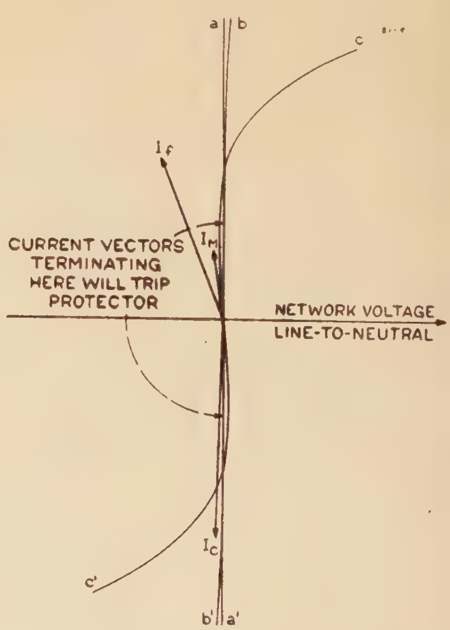


Figure 9. Network master relay tripping characteristics

I_c—Cable charging current
I_f—Short-circuit current
I_M—Transformer exciting current

Five Years' Experience With Ultrahigh-Speed Reclosing of High-Voltage Transmission Lines

PHILIP SPORN
FELLOW AIEE

C. A. MULLER
MEMBER AIEE

Synopsis: The data covering five years' operating experience with 33 ultrahigh-speed reclosing breaker installations mainly on a large interconnected and integrated high-tension system are presented and analyzed, and conclusions based on this experience are drawn. Out of 71 cases of flashover cited, 65 reclosures were successful and 6 cases of reclosure resulted in restrikes, a record of 91.5 per cent successful reclosures. The conclusions drawn are that not only is actual performance better than appeared possible when the development was first made but that further improvements are possible by further reducing breaker time.

I. Introduction

THE basic principles of ultrahigh-speed reclosing of high-voltage transmission lines have been previously presented[1] in a paper before the Institute. Likewise, operating experience with the original high-speed reclosing equipment first developed and with a modification of that equipment were presented[2] two years ago. However, the data available at that time covered only three sections (six terminals) of high-voltage transmission lines and a period of only three years, in one section of which the equipment was in service for only one year and another the equipment was in service for only a portion of one year, so that operating experience with only 15 cases of reclosure could be cited and discussed. Since then, however, the application of ultrarapid reclosure has not only been widely extended but a great many more operations have been experienced. These now constitute a set of data that is extensive enough to be able to furnish a basis for some well-founded conclusions. It is the purpose of this paper to present and analyze these data and draw such conclusions therefrom as are warranted and pertinent.

II. System on Which Installed

The system on which all terminal equipments with the exception of four (representing two line sections) have been installed is the central system of the American Gas and Electric Company. This is shown diagrammatically in figure 2. This system is an integrated system operating in seven states and comprising altogether 1,455 miles of 132-kv transmission, substantially all of which is of double-circuit steel-tower construction with a total, as of the date of writing, of 2,483 miles of circuit. It serves a load whose last-recorded maximum one-hour integrated peak was 997,000 kw. On this system the power supply, that is, power generation and power transmission to load centers, is integrated and co-ordinated to the highest degree. The system, which is a predominantly steam-electric system, nevertheless has a substantial portion of hydro capacity. Besides this, extensive and important foreign interconnections exist on several portions of the system through which diversity and other exchanges are carried out with adjacent systems. This, coupled with the diversities in load and, to some extent, of time over the system, makes imperative frequent and in many cases sudden changes in power flow over many of the important transmission lines on the system. Besides that, the availability of economical supplies of hydro in portions of the system and the concentration of generation by steam-electric stations at the points where combined optimum fuel and water conditions prevail, make economically desirable and necessary the transfer of heavy flows of power, at one time or another, over most of the transmission lines on the system. Under these conditions, the importance of continuity of supply, if the entire system is to operate in accordance with predetermined principles of economy, is apparent. Hence, the first and so far the widest application for ultrahigh-speed reclosing has been found on that system.

The four remaining terminals not installed on the central system are on the double-circuit Deepwater-Atlantic City lines of the South Jersey system. These two circuits are installed on 132,000-volt towers and insulated for that voltage but are operating at present at a voltage of 66 kv.

The first installation using the experimental equipment was on the Fort Wayne-Deer Creek circuit in Indiana. As will be noted from the diagram, since then 27 additional terminals (13 line sections) on the system have been installed covering a total circuit mileage of 655 miles. These have been extended progressively as the need for them arose and as the operating advantages or necessities were indicated.

III. Operating Experience

A summary of the total operating experience since the first installation is given in table I. Referring to that table it will be seen that taking the two systems which the record covers, a total of 33 terminals involving 16 line sections have been covered, and that these 16 line sections cover approximately 840 circuit miles of line, all but 126 of which operate at 132,000 volts. In the period May 1936 to November 1940, covering substantially five lightning years, 72 cases

Paper 41-52, recommended by the AIEE committees on power transmission and distribution and protective devices, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 16, 1940; made available for preprinting December 12, 1940.

PHILIP SPORN is vice-president and chief engineer, and C. A. MULLER protection engineer, for the American Gas and Electric Service Corporation, New York, N. Y.

1. For all numbered references, see list at end of paper.

---

3. The tripping characteristics have been improved to permit operation at normal voltage over a wider range of highly lagging and highly leading currents.

4. There have been many mechanical improvements in network relays which have improved their performance and reduced maintenance.

References

1. LOW VOLTAGE A-C NETWORKS, D. K. Blake. *General Electric Review*, February to November 1928, inclusive.

WHEN TO START A NETWORK, D. K. Blake. *Electrical World*, volume 95, February 15, 1930, page 347.

HOW TO START A NETWORK, D. K. Blake. *Electrical World*, volume 96, July 19, 1930, page 115.

2. WHERE TO USE LIGHT-DENSITY NETWORKS. D. L. Beeman. *Distribution*, July 1939, pages 10–11.

3. LIMITATIONS ON SETTINGS OF NETWORK RELAYS, D. L. Beeman. *Distribution*, January 1940, page 13.

4. A SINGLE-ELEMENT POLYPHASE DIRECTIONAL RELAY, A. J. McConnell. AIEE TRANSACTIONS, volume 56, 1937 (January section), pages 77–80 and 113.

of flashover resulting in line opening occurred. Of these, 63 cases were single-line trouble and 9 cases were two-line trouble. Out of the same number of 72 cases of flashover, 65 reclosures were successful and 7 cases of reclosure resulted in restrikes. This is a record of 9.7 per cent unsuccessful reclosures; but in this connection it needs to be pointed out that in one of these cases permanent physical damage had previously resulted to a tower and that under such conditions obviously successful reclosure was a physical impossibility since nothing but a permanent outage could clear the trouble. Disregarding, therefore, this one case, the total unsuccessful reclosures were six, representing a percentage slightly over eight per cent. An interesting thing in this connection, too, is that in not a single case did the equipment fail mechanically, that is, the mechanical performance was in every case perfect and reclosure was carried through and was successful in every case where the circuit condition permitted re-energization of the line. Table I shows clearly, too, the rapid accumulation of experience with the year 1940. It will be noted that the percentage of restrikes or unsuccessful reclosures for 1940 was again slightly over eight per cent, the same figure as for the total five-year period.

The table further shows the distribution of faults between phase to ground, phase to phase and ground, and three phase. Of the 71 cases of flashover, 55 cases were phase-to-ground faults on one line with 53 successful reclosures and only two restrikes which were probably due to multiple lightning stroke as explained in previous paper.[2] Three cases of phase-to-phase and ground faults on one line occurred, all of which reclosed successfully. Five cases of three-phase faults on one line occurred with three successful reclosures and two restrikes. Three cases of phase-to-ground faults on two lines occurred, all of which reclosed successfully. Four cases of phase-to-phase and ground faults on two lines occurred with three successful reclosures and one restrike. One case of three-phase fault on two lines occurred which restruck.

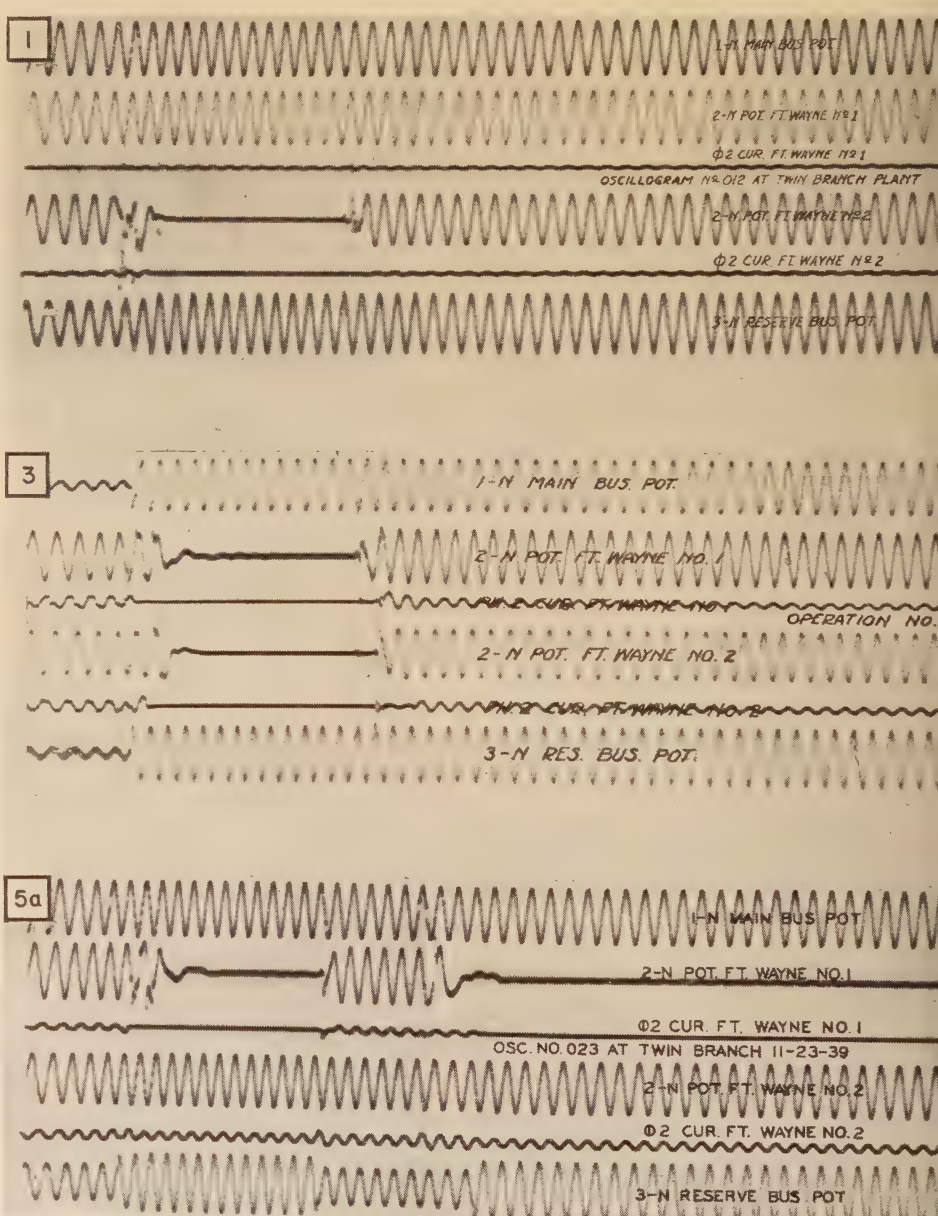
IV. Some Typical Oscillograms and Their Significance

In figure 1 are shown five sets of oscillographic records taken at Twin Branch station showing system performance for five typical cases of trouble on the system. The top and bottom traces on all oscillograms represent phase 1-to-neutral and phase 3-to-neutral voltages respectively on 132-kv bus at Twin Branch station. The second and fourth traces from the top indicate phase 2-to-neutral voltages of number 1 and number 2 Twin Branch-Fort Wayne lines respectively taken on the line side of the breakers at Twin Branch station. The third and fifth traces from the top represent phase 2 line currents on number 1 and number 2 Twin Branch-Fort Wayne lines respectively.

Oscillogram number 1 is a record of a lightning flashover on number 2 Twin Branch-Fort Wayne line involving phase 3 to ground that occurred at 9:34 p.m. on July 22, 1939. The fault was cleared in approximately $6^1/_2$ cycles and after a line de-energization of 12 cycles, reclosure was entirely successful.

Oscillogram number 2 is a record of a lightning flashover on number 1 Twin Branch-Fort Wayne line involving phase 1 to ground that occurred at 2:21 p.m. on June 18, 1940. The fault was cleared in approximately eight cycles and after a line de-energization of seven cycles, the line was re-energized from one end and three cycles later the breaker at the other end reclosed. The difference in reclosing times of the two breakers was due to the experimental adjustment of breaker-contact operating speed which existed at this time. With this adjustment the breaker contacts reached a point five-eighths inch from contact "make" position after 15 cycles and hesitated at this point, completing the stroke at 18 cycles. It is believed that when the five-eighths inch point was reached, the breaker at one end of the line arced across its contacts, thus energizing the line. As soon as the line was energized, most of the potential

Figure 1. Oscillograms of actual operation on the 132-kv transmission system of the central system

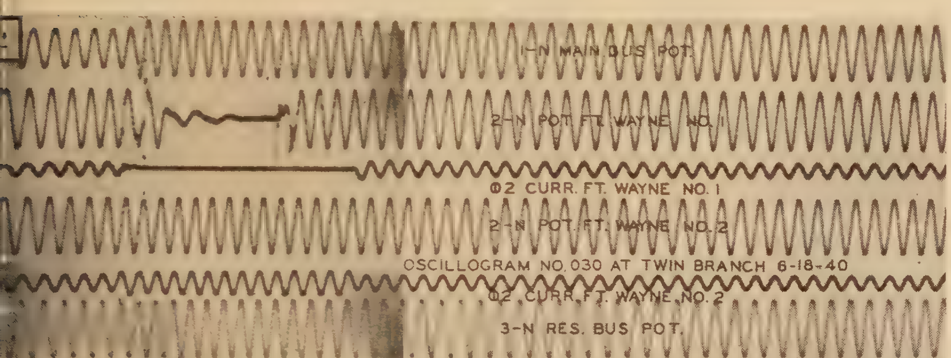


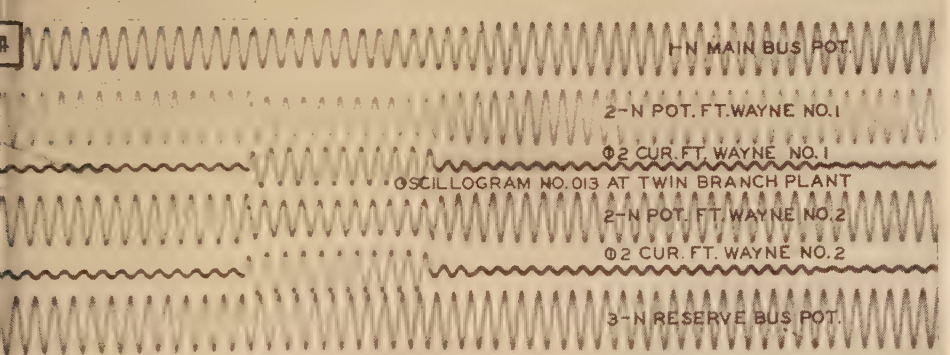
across the contacts of the breaker at the other end disappeared and the circuit was therefore not closed until electrical contact was finally made by the second breaker at 18 cycles.

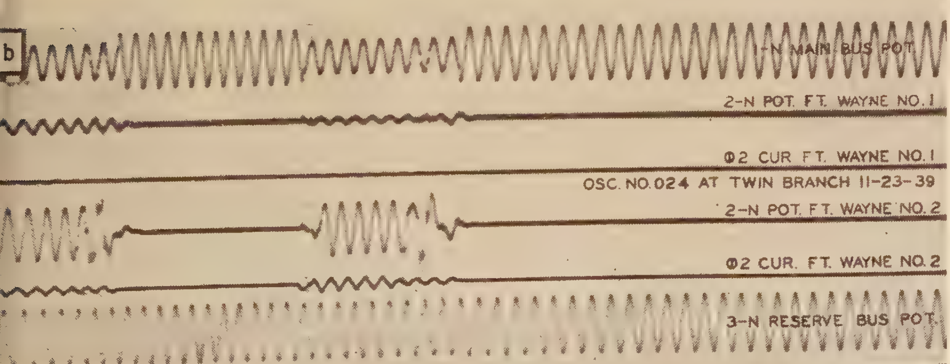
Oscillogram number 3 is a record of lightning flashover occurring simultaneously on number 1 and number 2 Twin Branch-Fort Wayne lines involving phases 1 and 3 to ground that occurred at 12:50 a.m. on July 8, 1939. Both lines were opened at both ends in approximately $6^1/_2$ cycles after the inception of the fault and after both lines had been de-energized for $11^1/_2$ cycles, reclosure of all four breakers on both lines was entirely successful.

Oscillogram number 4 is a record of lightning flashover occurring simultaneously on Fort Wayne-Deer Creek and Fort Wayne-Delaware lines involving phases 1 and 2 to ground that occurred at 12:13 a.m. on July 23, 1939. At this time the Fort Wayne-Deer Creek line only was equipped with ultrahigh-speed reclosing equipment, which line reclosed successfully. The Fort Wayne-Delaware line was only protected with instantaneous overcurrent relays in conjunction with time-delay overcurrent relays. Under these conditions, it is to be noted that both lines opened up at both ends $10^1/_2$ cycles after the inception of the fault.

Oscillogram number 5 is a record taken when mechanical damage occurred to a steel tower on number 1 and number 2 Twin Branch-Fort Wayne lines at 9:54 p.m. on November 23, 1939. From the oscillogram it will be noted that a fault involving phase 3 to ground occurred first on number 1 line, which opened at both ends $7^1/_2$ cycles after the inception of the fault and reclosed after de-energization of the line for ten cycles and reopened due to permanent trouble on the line section. Approximately 30 cycles later number 2 line became involved in the trouble with phase 1 going to ground, opening both ends after $6^1/_2$ cycles and reclosing after line had been de-energized 12 cycles when it retripped on account of permanent trouble on the line section.







V. Additional Installations

The accumulated operating experience has been so beneficial and the results obtained so much greater than even the authors originally anticipated that as the continuity problem and the problem of reliability of supply had to be met on other sections of the system, ultrarapid reclosure was extended and is still being extended today. Thus at the present time there are 12 additional terminals in process of installation covering additional 6 line sections with a total 224.2 miles of 132-kv circuit. These are clearly indicated in the diagram figure 2. Other points on the central system, and on the other two systems of the American Gas and Electric Company where the same general problem is being studied, are being seriously considered for equipment with ultrarapid reclosure on the terminal breakers and there is no doubt in the authors' minds that such additional applications will be found desirable and/or necessary. Particularly is attention being given to medium-voltage lines in the subtransmission or distribution class such as those of 23,000-volt and 33,000-volt rating. Here, however, the problem that still has to be solved is the one of providing an economical reclosing mechanism and a relay arrangement that will combine the basic elements of one cycle differential operation without the expense involved in the present system. While neither of these two problems has been entirely worked out the present indications are that both can and will be.

VI. Conclusions

Based upon the five years' experience studied and discussed here the authors believe that the following conclusions are clearly indicated:

1. In general on a high-voltage system properly insulated and provided with ground-wire protection at least 90 per cent successful reclosure can be expected by the use of ultrarapid reclosing. In the case of the two systems cited and discussed, out of 72 operations 71 were apparently due to lightning and of these 65 reclosures were successful. This is a record of better than 91 per cent successful operation and compares with the previously indicated figure of not less than 75 per cent successful operation.

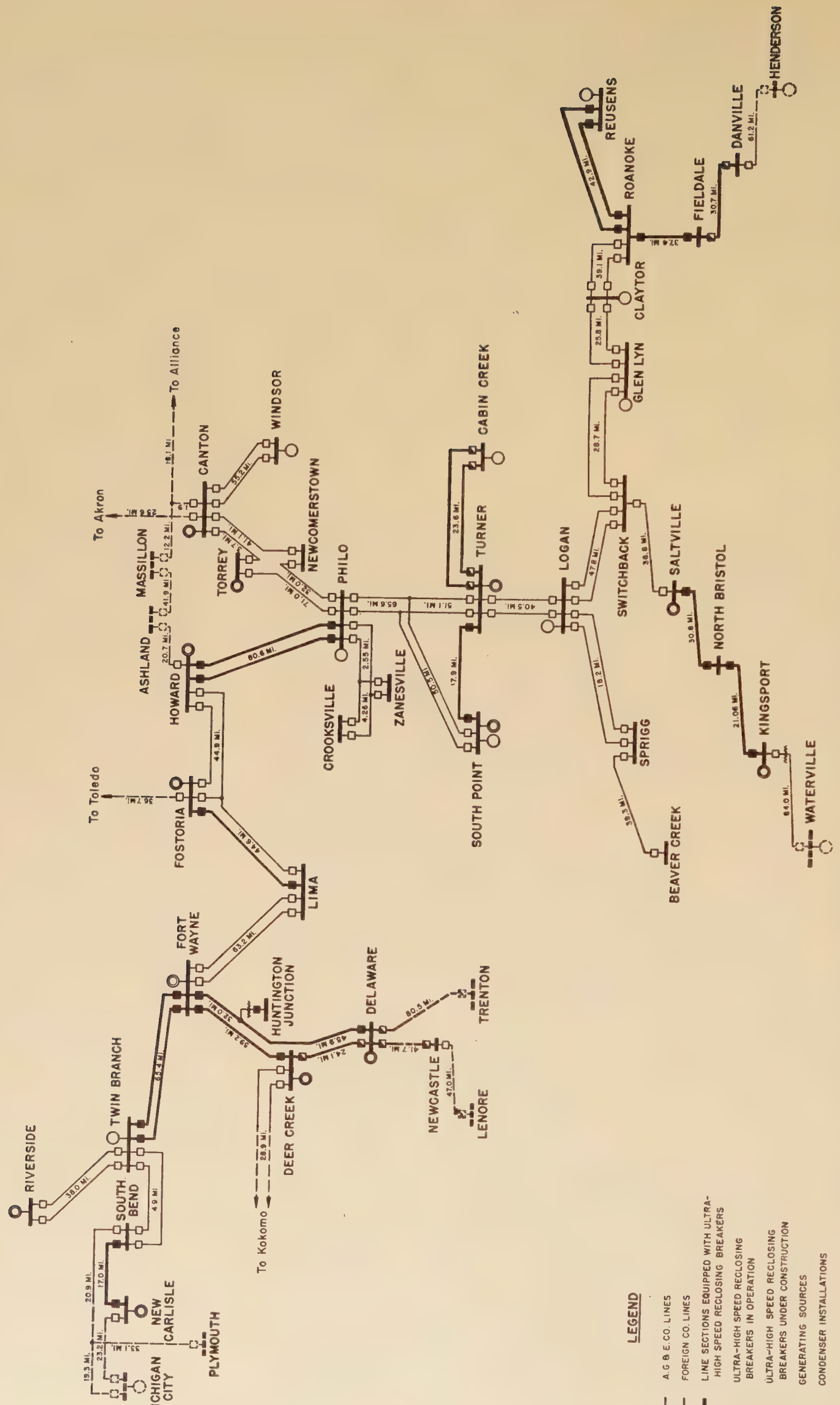


Figure 2. Ultrahigh-speed reclosing oil circuit breaker installations on the 132-kv transmission system of the central system of the American Gas and Electric Company

Table I. Summary of Actual Operations of 132-Kv Ultrahigh-Speed Reclosing Oil Circuit Breakers, May 1936 to November 1940

Line	Line Voltage (Kv)	Length of Line (Circuit Miles)	Number of Terminals Involved	Date of Installation	Ultrahigh-Speed Oil Circuit Breaker Operations: Number of Operations						Number of Successful Reclosures						Number of Restrikes						Types of Faults: Phase to Ground						Phase to Phase to Ground						Three Phase					
					1936	1937	1938	1939	1940	Total	1936	1937	1938	1939	1940	Total	1936	1937	1938	1939	1940	Total	1936	1937	1938	1939	1940	Total	1936	1937	1938	1939	1940	Total	1936	1937	1938	1939	1940	Total
Fort Wayne-Deer Creek	132	59.2	2	5/17/36	4	5	3	1	3	16	3	4	3	1	3	14	1	1				2	4	5	3	1	3	16												
South Bend-New Carlisle	132	17.0	2	1/29/38			1	1		2			1	1		2									1	1		2												
No. 1 Twin Branch-Fort Wayne	132	65.4	2	8/31/38				1	2	3				1	2	3										1	2	3												
No. 2 Twin Branch-Fort Wayne	132	65.4	2	7/25/38			2	3	1	6			2	3	1	6									2	3	1	6												
Nos. 1 and 2 Twin Branch-Fort Wayne	132		4	8/31/38				2		2				1		1				1		1										1		1				1		1
Fort Wayne-Delaware	132	77.9	3	5/26/40					1	1					1	1											1	1												
Saltville-North Bristol	132	30.8	2	3/22/40					6	6					6	6											3	3					1	1					2	2
North Bristol-Kingsport	132	21.1	2	3/20/40					6	6					4	4					2	2					3	3											3	3
Roanoke-Fieldale	132	37.35	2	4/28/40					12	12					12	12											10	10					2	2						
No. 1 Roanoke-Reusens	132	42.89	2	5/ 1/40																																				
No. 2 Roanoke-Reusens	132	42.89	2	5/ 1/40					3	3					3	3											3	3												
Nos. 1 and 2 Roanoke-Reusens	132		4	5/ 1/40					6	6					4	4					2	2					3	3					3	3						
No. 1 Philo-Howard	132	80.6	2	5/ 2/40					3	3					3	3											3	3												
No. 2 Philo-Howard	132	80.6	2	5/20/40					3	3					3	3											3	3												
No. 1 and No. 2 Philo-Howard	132		4	5/20/40																																				
Fostoria-Lima	132	44.6	2	10/3/40																																				
No. 1 Deepwater-Atlantic City	66	63.1	2	6/27/40																																				
No. 2 Deepwater-Atlantic City	66	63.1	2	6/27/40					2	2					2	2											2	2												
Nos. 1 and No. 2 Deepwater-Atlantic City	66		4	6/27/40					1	1					1	1																	1	1						
Turner-South Point	132	47.94	2	8/ 1/40																																				
Total		839.87	33		4	5	6	8	49	72	3	4	6	7	45	65	1	1	..	1	4	7	4	5	6	6	37	58	..	..	..	1	7	8	..	..	..	1	5	6

An Improved Polyphase Directional Relay

BERT V. HOARD
MEMBER AIEE

THE inductor-loop principle of operation has been employed successfully for many years in building single-phase directional relays of the high-speed type. This principle of operation has now been extended to obtain a high-speed polyphase directional relay of a radically different type of construction than has been employed heretofore, which has such features as simplicity, compactness, low burden, high sensitivity, and nonbounce contacts.

The trend toward high-speed operation for all types of protective-relay applications has developed a need for such a relay. This is particularly true in directional-comparison schemes of pilot relaying. Other applications include the use of a polyphase directional element with instantaneous overcurrent or impedance relays and for these applications high speed in the directional element is needed for proper co-ordination.

The principle of operation of the inductor-loop element is that of a conductor carrying current in a magnetic field. The inherent efficiency and simplicity of the magnetic circuit combined with low inertia of the inductor loop makes possible a directional-relay design having a high torque-to-weight ratio which is essential if sensitive, high-speed operation is to be obtained.

The arrangement of the components of such a relay element designed for three-phase operation is shown schematically in figure 1. It consists of three electromagnets and three loops around a vertical shaft. Each loop is mounted on the shaft with its outer side located in an air gap within the electromagnet. The voltage coils, one on each of the outer two legs of each electromagnet, have a voltage applied which induces a large current in the loop by transformer action. Current flowing through the current coil, which is located on the center leg of the electromagnet, produces an air-gap flux which interacts with the loop current in the outer side of the loop and causes rotation of the shaft in a direction corresponding to the flow of alternating current power. If the direction of current flow reverses, the torque and the direction of rotation of the shaft reverse. A photograph of the relay is shown in figure 2.

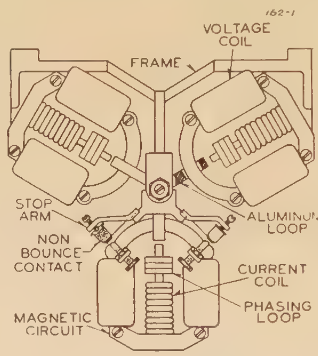


Figure 1. Diagram of electromagnets, loops, and contacts

The phase-angle characteristic of the inductor-loop electromagnet is essentially that of a watt element, although maximum torque is obtained when the applied current is slightly lagging the voltage. In the voltage circuit the loop can be considered as the secondary load of a transformer which has a high resistance compared to its reactance, so that the loop current lags the primary voltage by an angle of about 15 degrees. In the current circuit the air-gap flux is in phase with the applied current. When loop-current and air-gap flux are in phase, maximum torque is obtained, hence this condition is fulfilled when the applied current lags the voltage by 15 degrees.

One loop and its associated electromagnet make up one phase of the three-phase relay, and a delta voltage and a star current are applied. For actual installations, the 90-degree connection is normally used for polyphase directional relays because during phase-to-phase faults more sensitive operation will be obtained, since the two elements carrying fault current have the two unfaulted

Figure 2. Photograph of H-3 relay with glass cover removed

Paper 41-62, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 18, 1940; made available for preprinting December 13, 1940.

BERT V. HOARD is relay development engineer for the Westinghouse Electric and Manufacturing Company, Newark, N. J.

---

2. The probability of restrike on double-circuit lines of the type existing on the central system in case of double-circuit flashovers is approximately four times as great as in the case of single-circuit flashovers. Thus, in the case of the two systems described, out of eight cases of two-line trouble (omitting the one due to permanent disability) two restrikes occurred or a restrike record of 25 per cent. On the balance of 63 cases of one-line flashover, four restrikes occurred or a restrike record of 6.5 per cent.

3. Ultrarapid reclosure has definitely established itself as an indispensable tool in high-tension integrated power systems. A definite start has been made in the direction of extending it to lower voltage lines. Further development here is needed and will depend upon the successful removal of the economic limitation to the extension of this application to such lower voltage and, therefore, lesser capacity lines.

4. There is reason to believe that the present 8.5 per cent unsuccessful operation can be reduced and particularly that the percentage of 25 per cent failure to reclose successfully on two-line faults can be reduced. The means for carrying this out so far indicated are as follows:

(*a*). Reducing the total percentage of two-line flashovers by further increasing the speed of clearing of the fault.

(*b*). Reducing the percentage of restrikes by speeding up the clearing time and thus permitting a corresponding increased waiting time before reclosure is attempted.

References

1. ULTRA-HIGH SPEED RECLOSING OF HIGH VOLTAGE TRANSMISSION LINES, Philip Sporn and D. C. Prince. AIEE TRANSACTIONS, volume 56, 1937, pages 81–90.

2. EXPERIENCE WITH ULTRA-HIGH SPEED RECLOSING OF HIGH VOLTAGE TRANSMISSION LINES, Philip Sporn and C. A. Muller. AIEE TRANSACTIONS, volume 58, 1939, pages 625–31.

delta voltages applied to them, respectively. Using this connection, one of the electromagnets will have line current from phase *a* and the delta voltage opposite phase *a* applied. Thus, for unity power factor in the system, the current through the relay electromagnet is leading the applied voltage by 90 degrees, and for a fault which causes the system current to lag by 45 degrees the relay current leads the applied voltage by 45 degrees.

For the 90-degree connection the relay phase-angle characteristic should, therefore, be shifted so that maximum torque is obtained when the relay current leads the relay voltage by 45 degrees. A series resistance-phase shifter, similar to that commonly used in the induction-disk type relay cannot be used for the inductor-loop relay, because the latter has a voltage circuit which is mostly resistance. However, a series capacitor of the proper size will produce the 45-degree phase-angle characteristic as shown in the diagram of figure 3*a*.

A simpler phase shifter and one that is better from an operating and maintenance standpoint is the use of a phasing loop on the magnetic circuit in front of the current coil as shown in figure 1. The phasing loop consists of three heavy rectangular-shaped copper washers and causes the air-gap flux to lag behind the applied relay current, so that the current must be advanced in phase position to bring the loop-current and air-gap flux back in phase and obtain maximum torque. This type of phase shifter is used on the relay to obtain a 45-degree characteristic as shown in figure 3*b*. To obtain the same magnitude of air-gap flux and relay sensitivity, a larger number of turns are used on the current coil when phasing loops are used. Even with the increased number of turns required, the burden of the current circuit is very low as shown subsequently.

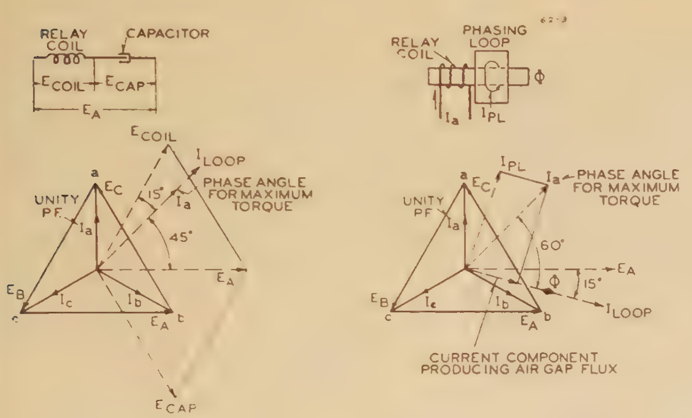


Figure 3. Vector diagram for phase (a) electromagnet using 90-degree connection

(*a*)—Using capacitor phase shifter in potential circuit to obtain maximum torque in relay when system-fault current lags by 45 degrees

(*b*)—Using phasing-loop phase shifter in current circuit, to obtain maximum torque in relay when fault current lags 45 degrees

The instantaneous torque in any one electromagnet of the relay is produced by the instantaneous products of voltage (loop current) and current (air-gap flux) in the electromagnet, which is a double-frequency pulsating torque. Figures 4*a* and 4*b* show this torque respectively for phase angles when the average torque is a maximum and when it is zero. The torques in the other two electromagnets are also pulsating as shown, respectively, in figures 4*c* and 4*d*; however, they are displaced 120 degrees in time phase from each other and when all three instantaneous values are added up, the result is a uniform nonpulsating torque. Hence, under normal conditions with the three applied currents and voltage balanced there is no tendency for these torques to cause vibration. During unbalanced faults, in general, there will be a combination of a balanced torque and a pulsating torque on the moving element and the pulsating torque will tend to produce some vibration. However, this vibration has been minimized through proper moving element and contact design which keeps the contacts positively closed when the unbalanced torque is present.

The contact travel for any type of high-speed relay is necessarily small as one means of obtaining high speed. For this relay, due to its extremely high ratio of torque to inertia, the normal travel of 0.030 inch is greater than has been customarily used in the past for similar relays. Nonbounce contacts are used, which consist of a small enclosed cylinder partially filled with tungsten powder mounted on the end of a flexible spring. When the cylinder strikes the rigid stationary contacts, the particles of tungsten slide over each other and absorb the energy of impact. After the contact spring has been slightly deflected, the adjusting screw in the stop arm (figure 1) strikes the moving contact cylinder and then the full torque of the relay is transmitted to the moving and fixed contacts. Hence, the contacts act as the moving-element stop and full contact pressure is assured at all times. Connection is made to the moving contact by means of a very flexible copper-conducting strip.

Among the advantages obtained because of the loop type of construction is that large air gaps can be used between iron and loop which makes the element easy to inspect and eliminates the possibility of air-gap friction from foreign materials lodging in the gap. The efficiency of the design is such that very small burdens per phase are imposed. The voltage circuit requires 4.0 volt-amperes per phase at 115 volts and the cur-

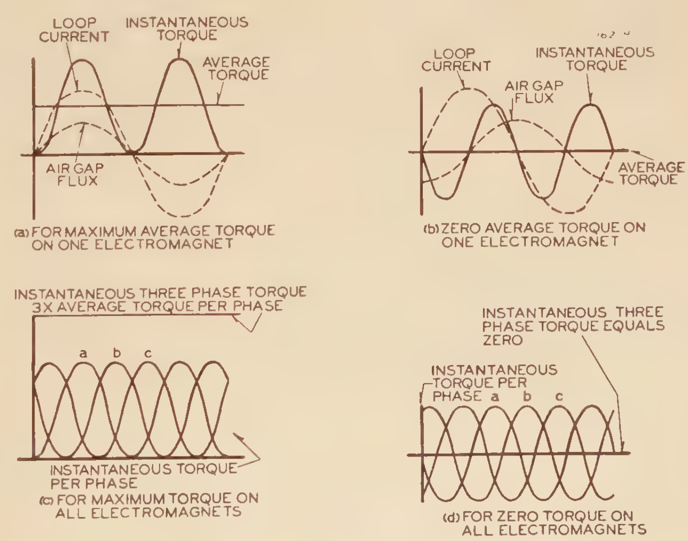


Figure 4. Torques produced in polyphase directional relay

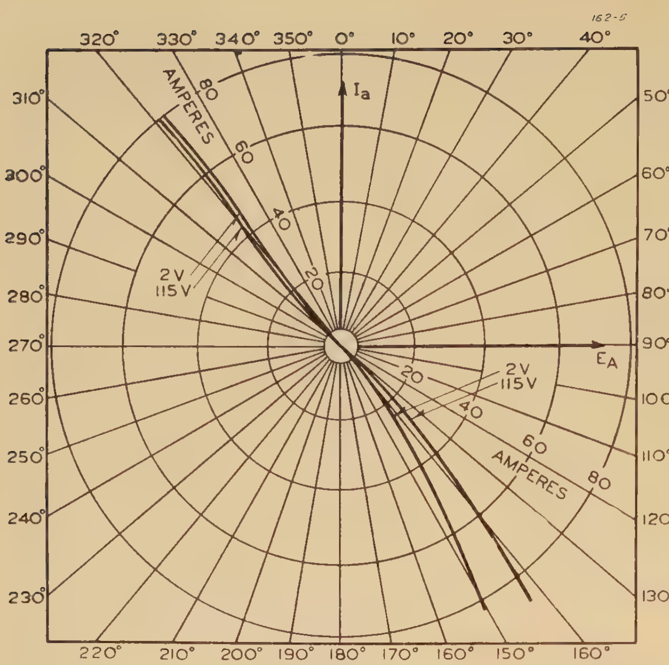


Figure 5. Phase-angle curves at 115 and 2 volts

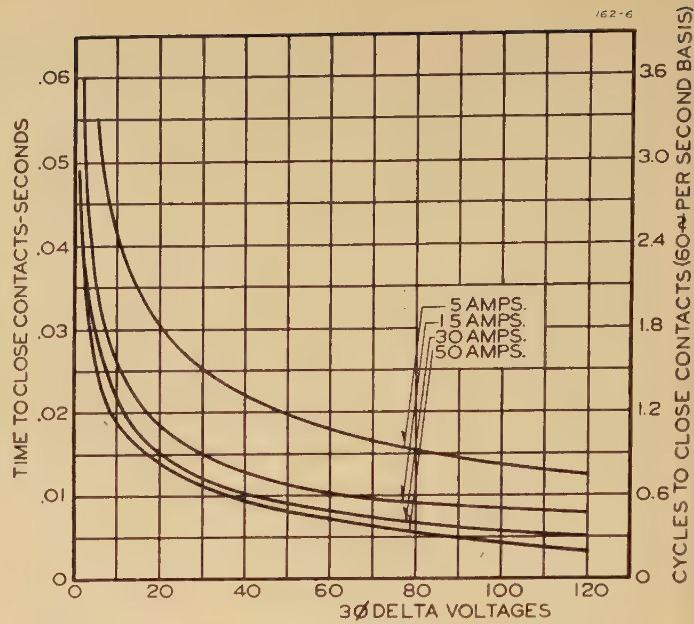


Figure 6. Timing curves of type H-3 directional relay

rent circuit, which also includes the phasing loops, requires 1.6 volt-amperes per phase at five amperes. The sensitivity of the relay is excellent, being less than one volt over a current range of 2.5 amperes to 100 amperes at the maximum torque phase angle. From the phase-angle curves shown in figure 5 it will be seen that the relay has adequate directional characteristics even at a very low voltage and high current.

Timing curves for the relay taken with a 0.030-inch contact gap are shown in figure 6. It will be seen that at 65 volts and above 15 amperes the timing is less than 0.6 cycle on a 60-cycle basis.

The directional relay is also made with a voltage-restraint element as shown in figure 7. The restraint element is mounted below the directional element and consists of three electromagnets and loops similar to those used on the directional element. However, the outer coils of each electromagnet are energized from one delta voltage, and the center coil is energized from another delta voltage. The phase-angle characteristic of the electromagnet is such that the torque of the element is proportional to:

$E_1E_2 \sin \theta$

where θ is the angle between the two delta voltages and is normally 60 degrees.

Each electromagnet is connected to a

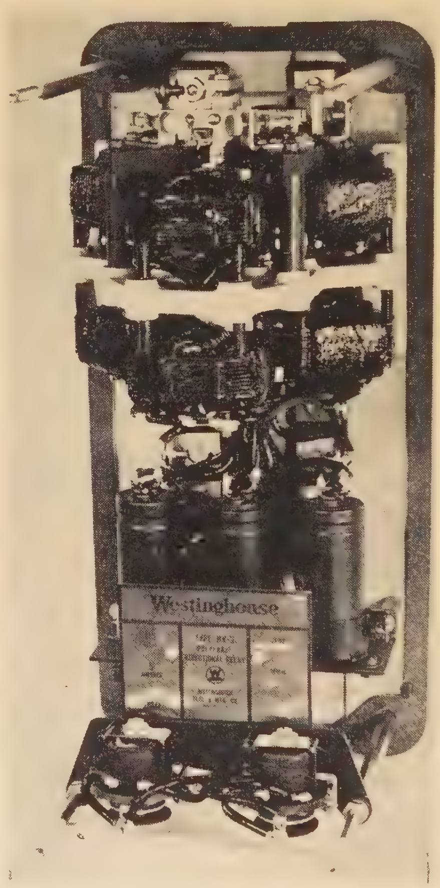


Figure 7. Photograph of HV-3 relay with glass cover removed

different combination of delta voltages so that a uniform restraint torque and balanced burdens are obtained. During a three-phase fault the voltage-restraint torque is reduced in proportion to the square of the voltage, so that for low voltages it is negligible. During unbalanced faults when any one delta voltage becomes zero, the restraint is automatically removed, because one of the applied voltages becomes zero on two of the electromagnets, and on the third electromagnet the collapsed voltage has made the sine of θ zero.

If it is desired to remove the restraint during a fault, it can easily be accomplished by opening any one supply lead to the restraint element. This applies single-phase voltage to all three electromagnets and the sine of θ becomes zero on all, so that there is no torque on any of them. The restraint is such that it requires ten amperes at normal voltage at the maximum torque phase angle of the directional relay to overcome the restraint torque.

In conclusion, the new polyphase inductor-loop directional relay has all the desirable characteristics inherent in the induction-disk type relay, with the additional ones of compactness, low burden, high sensitivity, and high-speed operation, which is difficult to obtain with the polyphase induction-disk type. With these outstanding advantages, it is believed that the new relay will replace the polyphase induction-disk type where formerly used and will be considered as an important advancement in relaying art.

Transactions Section

Preprint of Corresponding Pages From the Current Annual Transactions Volume

Any discussion of these papers will appear in the June 1941 "Supplement to Electrical Engineering—Transactions Section"

Experience With Preventive Lightning Protection on Transmission Lines

S. K. WALDORF
MEMBER AIEE

Synopsis: Footing resistances for transmission line towers must be low for good operation, but it appears that no benefit results from reducing them below a certain limiting value characteristic of a given construction. This is because flashover can apparently be caused not only by excessive footing resistance drop, but also by the reactive drop accompanying rapid rates of current rise when tower currents are large.

The records seem to show that overhead ground wires provide better shielding than has been believed. Overhead ground wires and tower footing resistances co-ordinated with line insulation provide preventive protection which is highly efficient.

Operating experience indicates that lightning outages can be predicted fairly well from simple probability calculations.

I. Introduction

THE art of protecting transmission lines against lightning has advanced considerably in the last decade, but there are some phases of the problem which are still obscure. In analyzing the experience of the Pennsylvania Water and Power Company, which operates steel tower transmission lines at 66 to 220 kv, certain trends have appeared which are believed to be significant. It is the purpose of this paper to bring these findings to the attention of those interested in lightning protection in order that the apparent trends may be widely investigated and their validity established or disproved. The interpretation of results as given here, therefore, in no sense should be considered as final, but only as bases for further study.

Preventive lightning protection for transmission lines, as the term implies, is designed to prevent flashovers entirely as contrasted to remedial measures which are designed to minimize the effects of lightning. In this paper, preventive lightning protection is used in a special sense as the designation for the mounting of overhead ground wires on the same steel towers as the power conductors and the co-ordination of tower footing resistances with line insulation. Tower footing resistances on the lines referred to here have been almost exclusively reduced by the installation of buried counterpoise conductors of various lengths and number.

II. Extent of Experience

The Pennsylvania Water and Power Company first began to try preventive lightning protection on its transmission lines in 1931 with the construction of the Safe Harbor-Westport 220-kv line.[1] Since then two new lines have been constructed and five old ones improved using the same basic principles, but with variation in details.

In 1934, surge-crest ammeter links[2] were installed on the Safe Harbor-Westport-Takoma 220-kv line and since then their use has been gradually expanded until in 1939, 2,279 transmission towers on 318 miles of line have been equipped. These devices have permitted a relatively close check to be made of the efficiency of the lightning protection.

Surge-crest ammeter links have also been placed on 21 banks of 66-kv lightning arresters, two banks of 132-kv arresters, and one bank of 220-kv arresters.

III. Distribution of Current in Tower Members

For several years, there has been a total of 87 towers equipped with a pair of surge-crest ammeter links on each of the four corner or leg members of each tower. Since 1934, 209 sets of records have been obtained from these installations, of which 98 records are from towers believed to have been struck by lightning or adjacent to struck spans. The purpose of these observations has been to determine the error entering into the assumption that the tower current is four times the current in one corner leg.

The results of this study are given in table I. The sum of the four indications in the corner legs has been taken as the approximately correct tower current. The deviation from it of four times each of the four individual leg currents has been obtained. The deviations for each group of tower records in 5,000-ampere increments of tower current have been averaged in table I.

Although relatively few readings have been obtained when the tower currents were of the larger magnitudes, from table I it appears that the indications obtained on towers having a bracket on only one leg can be assumed to be fairly good approximations when the currents are in

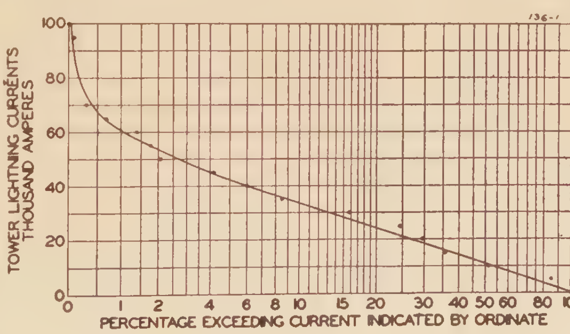


Figure 1. Distribution of 1,201 currents measured in towers believed struck by lightning (1934–39)

Paper 41-36, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted July 23, 1940; made available for preprinting December 10, 1940.

S. K. Waldorf is test engineer for the Pennsylvania Water and Power Company, Baltimore, Md.

1. For all numbered references, see list at end of paper.

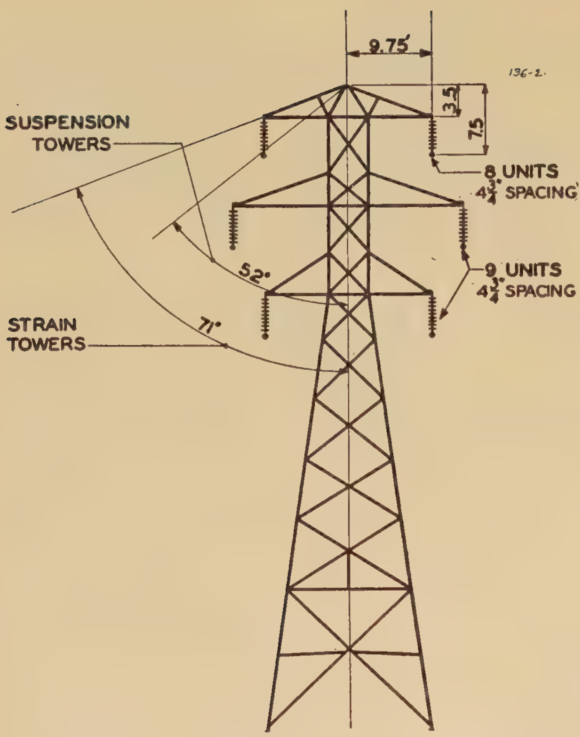


Figure 2. Minimum shielding zones required of single overhead ground wire on suspension and strain towers of the Holtwood–Coatesville 66-kv line

the upper range, that is, greater than about 40,000 amperes.

In 45, or 22 per cent of the 209 sets of observations, the magnetic links on all legs of a tower did not have the same polarity of magnetization. It is believed that records of this type are due to successive strokes of opposite polarity, occurring either close together or with an appreciable elapsed time between them. As they have been found only in the lower current ranges, it is not likely that the large deviations in indication which they cause greatly affect the analyses given here.

It has been suggested that tower currents, as taken from records obtained in the four corner leg members of a tower, be multiplied by a factor ranging from about 1.3 to 2 to account for the current passing through the cross braces of the tower.[3] Because of the uncertainty of the value of the factor,[4] and the unequal distribution of lightning current in tower legs as shown in table I, none has been used in the data reported here.

IV. Distribution of Tower Currents of Various Magnitudes

In the period of 1934–39, a total of 1,201 tower currents has been recorded where it is believed that lightning struck. The tower current in each case was recorded as four times the current indicated in one of the four tower legs, or as the sum of the four indicated leg currents, depending upon the number of SCA links installed at the respective tower. The data have been plotted in figure 1.

V. Distribution of Lightning Strokes Along Lines

The records show that the 1,201 strokes which have terminated on the lines of the system have been well distributed. For instance, on the Safe Harbor-Perryville 132-kv line there were not over three consecutive towers which were not struck during the five-year period of the study. On the Safe Harbor-Westport-Takoma 220-kv line where the stroke records have been kept for six years, five is the maximum number of consecutive towers where no strokes have occurred. Although a considerable length of a line may not be struck during the first observation year, in general, it has been found that during succeeding years the maximum length of unstruck line is reduced to a few spans.

VI. Lightning-Stroke Frequency

In table II, the variations in frequency of occurrence of lightning are apparent. It will be noticed that the number of recorded strokes to a line will vary in the ratio of almost as much as three to one from year to year. During a year when the number of strokes to one line may be relatively high, those on another may be very low, as for instance, in the years 1935 and 1938. The average number of strokes per hundred miles of line per year is 126 for rights-of-way having only one line. This value cannot as yet be considered as final because the averages for the individual lines still deviate from it by as much as 29 per cent.

VII. Flashovers

Examination of the lightning current records of the Holtwood-Coatesville 66-kv line obtained during the three years before the installation of counterpoise re-

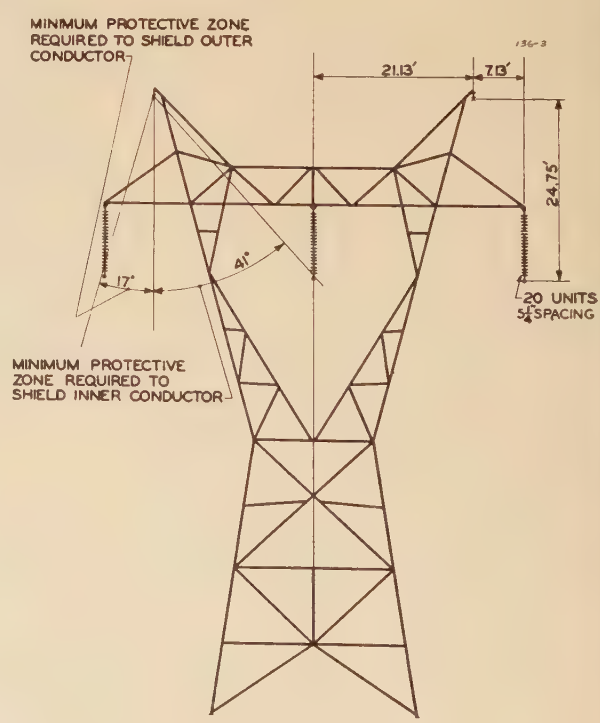


Figure 3. Minimum shielding required of overhead ground wires on 220-kv towers

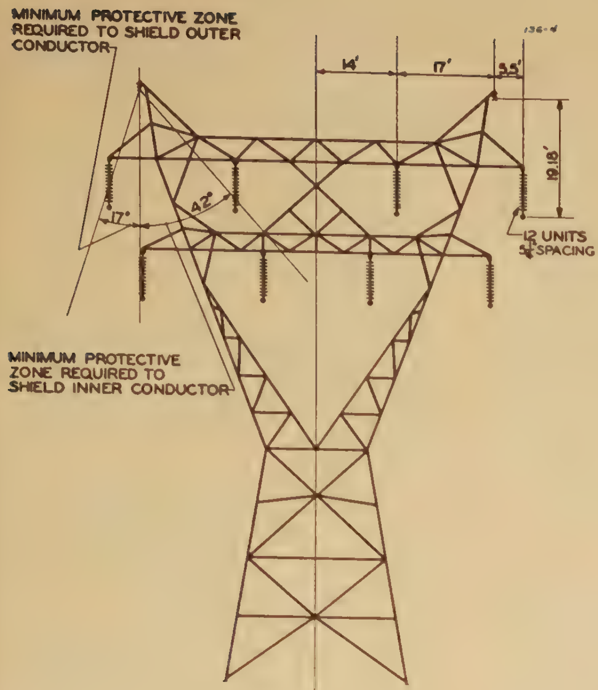
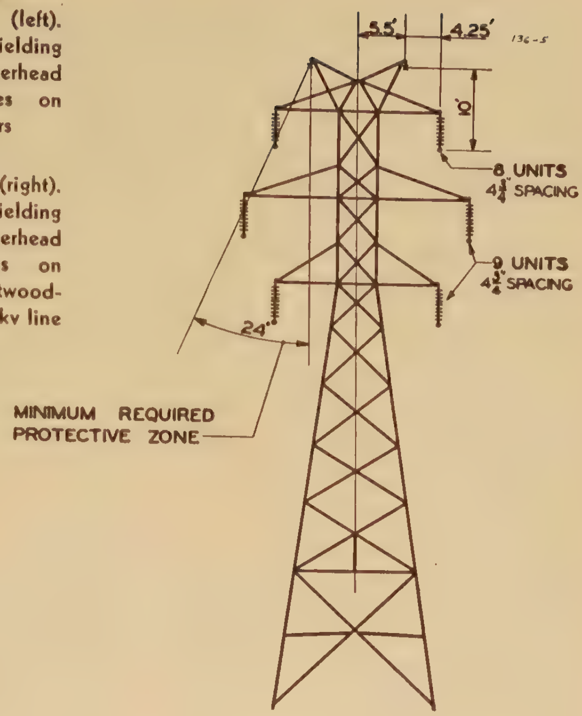


Figure 4 (left). Minimum shielding required of overhead ground wires on 132-kv towers

Figure 5 (right). Minimum shielding required of overhead ground wires on towers of Holtwood-York 66-kv line



veals no regular behavior. There were 21 single- and double-circuit tripouts during 1935, 20 during 1936, and 17 during 1937. The individual effects of poor grounding, insulation, and shielding are indeterminate from the data. However, after the installation of counterpoise and the improvement of insulation, the relative importance of the several protection factors became more apparent. The Holtwood-Coatesville line is the only line of the company on which surge-crest ammeter links were placed prior to the installation of counterpoise.

Data on the cases since 1934 in which flashover occurred on lines provided with preventive protection are given in table III.

It will be noticed that in six of the seven cases the indicated tower currents are greater than 50,000 amperes and in five of the cases they are of the order of 60,000 amperes. The latter group suggests that currents around 60,000 amperes are just above the maximum that can be carried without flashover by towers of the type used on the 66-kv lines. In 1937, a tower of the York line carried an indicated current of 63,200 amperes without flashover, which is the only case where a tower of the 66-kv lines carried current in excess of 50,000 amperes without flashover occurring. The tower footing resistance was seven ohms in this case, giving a calculated tower potential of 440 kv, 45 per cent of the normal safe maximum, or flashover level.

In the case of tower 99 of the Coatesville line in table III, it appears that the top conductor of circuit 13 was struck by lightning, causing the flashover. Tower 99 is a suspension tower.

These data on flashovers seem to show that there is a limiting current which towers can carry, irrespective of measured footing resistance. Due to recognized errors in the method of measurement of tower current, the results are not accurate, but a trend is indicated. For five out of six instances, flashovers occurred on 66-kv towers when tower currents were indicated in the order of 60,000 amperes. On the 132-kv line, the flashover recorded in table III was the only one which occurred in three cases where currents were in excess of 50,000 amperes. It is not clear whether the flashover was due to a combination of circumstances, the ground resistance of the counterpoise being relatively high within 300 feet of the tower (about $16^1/_2$ ohms) and a tall tower structure, or due to inadequate shielding. The available data seem to favor the first explanation.

The present-day theory[5] of the behavior of circuits carrying lightning surge currents indicates that there are two voltage effects present. One is the resistance drop which is at a maximum when the surge current is maximum, and the other is the reactance drop which is at its maximum when the current is changing most rapidly. These maxima obviously cannot occur at the same instant, but the maximum circuit voltage will occur somewhere in the interval between the instants of the maxima of the two component drop voltages. Either of the two may predominate, or their effects may be of equal importance, depending upon circuit conditions. From the flashover data presented here, it appears that when conditions are such as to give an indicated tower current of about 60,000 amperes, the rate of current change is sufficiently great to make the reactance component of drop appreciable. For towers, grounding, and insulation of the type used on the 66-kv lines considered, it apparently becomes predominant to the extent of almost always causing flashover. For towers, grounding, and insulation used on the 132-kv line, the reactive effect is appreciable, but apparently becomes of consequence only when tower heights and footing resistances are relatively great.

If future experience bears out the trend which now appears, there will be no advantage in reducing footing resistances below six or seven ohms for the type of 66-kv towers discussed here. Other types of construction will probably be found to have other values for the lowest worth-while limit of footing resistance.

VIII. Efficiency of Protection

The efficiency of a protective scheme can be computed by taking the ratio of the number of times strokes did not cause interruptions to the number of strokes. The efficiencies of the lightning protection during the years that the lightning current study has been in progress on the several lines are given in table IV. The true efficiencies may be slightly higher than those given in table IV because of

Table I. Deviation From Equal Division of Lightning Current in Tower Legs

Tower Current Range (Amperes)	Towers With Links of One Polarity: Cases	Towers With Links of One Polarity: Average Deviation (Per Cent)	Towers With Links of Both Polarities: Cases	Towers With Links of Both Polarities: Average Deviation (Per Cent)	All Towers in Range: Cases	All Towers in Range: Average Deviation (Per Cent)
1– 5,000	61	73	35	90	96	80
5,001–10,000	45	27	7	83	52	35
10,001–15,000	26	23	2	119	28	29
15,001–20,000	9	32	0		9	32
20,001–25,000	7	32	0		7	32
25,001–30,000	8	17	0		8	17
30,001–35,000	2	5	0		2	5
35,001–40,000	1	10	1	89	2	50
40,001–45,000	2	15	0		2	15
45,001–50,000	1	14	0		1	14
50,001–55,000	0		0		0	
55,001–60,000	1	6	0		1	6
60,001–65,000	1	6	0		1	6
Totals	164		45		209	

possible multiple records or weak records on the surge-crest ammeter links.

It is of some interest to note the extremely high efficiency of protection which is required to limit to a low figure the number of tripouts over a period of years.

IX. Efficiency of Shielding

The relative merits of one and two overhead ground wires and of the many possible positions in which they may be placed have been studied by many investigators at great length theoretically, and in the laboratory.[6] From the lightning current data which have been collected, it is possible to evaluate the efficiency under operating conditions of the various arrangements used on the lines to which reference is made here.

For an overhead ground wire to shield a line conductor from direct strokes, the line conductor must lie within the protective zone of the ground wire. In figures 2, 3, 4, and 5 are indicated the minimum protective shielding zones that the respective overhead ground wires must provide. Where a single overhead ground wire has been installed, the required protective zone is wider for a strain tower than for a suspension tower, as shown in figure 2. This is because the conductor is at the height of the cross arm on a strain tower, and below the cross arm on a suspension tower by the length of an insulator string. Where two overhead ground wires have been installed on the newer lines of the company, the overhead ground wires have been elevated at strain towers to maintain the same clearances above line conductors as is provided at suspension towers. The protective zones required on strain and suspension towers having such construction are, therefore, the same. (See figures 3, 4, and 5.)

From the number of flashovers and recorded strokes to the several classes of transmission lines, the minimum efficiencies of the shielding arrangements can be computed. The number of flashovers which have occurred are known accurately for practical purposes from the tripouts which have occurred. The recorded strokes to a line may be slightly less than the actual number due to more than one stroke affecting a set of links between inspections and calibrations. Ignoring some strokes because of the weak magnetic effect produced will also affect the number of reported strokes in the same manner.

When a flashover occurs, there may be some question of the cause being inadequate shielding or high-tower potential. If some flashovers are believed to be caused by excessive footing resistance or tower current, there will be less chargeable to imperfect shielding.

Efficiency of shielding =

$$100\left(1-\frac{\text{outages}}{\text{strokes}}\right)\text{per cent}$$

The maximum probable efficiency is obtained when the number of outages believed due to poor shielding is used in the expression, and the minimum efficiency when the total number of outages is used. The latter figure is, of course, the pessimistic one.

It can be seen in figures 3 and 4 that the shielding conditions on the 220-kv and 132-kv lines are practically identical. In table V the data for these two classes of towers are combined.

The behavior of the lines with two overhead ground wires is in agreement with the behavior predicted from surge tests on miniature models, but that of the line with one overhead ground wire is much better. In the latter case the shielding on the suspension towers is theoretically superior to that on the strain towers, but their behavior during the period of study has been practically the same.

X. Comparison of Calculated Probable Outages and Actual Outages

Some years ago Lewis and Foust[7] suggested that, as a result of their studies,

Table II. Strokes to Lines

Line	Length in Miles	Year	Recorded Strokes: In Year	Recorded Strokes: Average	Strokes Per 100 Miles: In Year	Strokes Per 100 Miles: Average
Safe Harbor-Westport-Takoma 220 kv	91.8	1935	115		125	
		1936	108		118	
		1937	87		95	
		1938	54		59	
		1939	118		129	
				96		105
Safe Harbor-Riverside 220 kv	50.5	1938	46		91	
		1939	45		89	
				46		90
Safe Harbor-Perryville 132 kv	31.5	1935	27		86	
	31.5	1936	69		219	
	31.5	1937	44		140	
	33.8	1938	56		166	
	33.8	1939	53		157	
				50		154
Holtwood-York 66 kv	22.8	1936	31		136	
		1937	41		180	
		1938	15		66	
		1939	22		97	
				27		120
Holtwood - Coatesville 66 kv	29.4	1936	30		102	
		1937	25		85	
		1938	68		232	
		1939	45		153	
				42		143
Holtwood - Baltimore 66 kv (2 lines) and Philadelphia Road-Gunpowder 110 kv	40 (of right-of-way)	1939	66		165	
				66		165

Average strokes per 100 miles of line per year for all lines except the last in the list is 126.

flashovers of shielded transmission lines only occur when tower potentials exceed the insulation strength of the given line. The tower potential in each case was taken as the product of tower footing resistance and tower lightning current. Based on this theory a method was suggested several years ago by the present writer for calculating the probable outages of shielded transmission lines.[8] In table VI a comparison is made between the actual flashovers experienced on the several lines and the calculated behavior.

For all but one of the lines, the actual performance has not been as good as the estimated. The record of flashovers given in table III shows that flashovers can be caused by tower currents less than those predicted from the theory based on tower footing resistance drop.

As the original empirical Lewis and Foust rule,[7] the data used in the probability calculations, and the records found when flashovers occurred are all based on the same measurement method, any discrepancies between calculated and actual outages do not seem to be attributable to neglecting the current carried by tower cross braces. The discrepancies are, therefore, thought to result from the impedance drop in the tower structure and footings being appreciable.

To make the probability calculations conform to field experience, the theory must be modified to state that flashover does not occur unless the product of tower current and tower footing resistance exceed the insulation level of the line, or unless the tower current exceeds the characteristic safe current for the given tower and grounding arrangement. The characteristic safe current seems to be around 60,000 amperes for the 66-kv lines. From the circumstances attending the single flashover which occurred on the 132-kv line, from the relative insulation strengths of the 66- and 132-kv lines, and from other data, it is estimated that the characteristic safe current of this 132-kv line is probably around 90,000 to 100,000 amperes. Experience with the 220-kv lines seems to indicate that the safe characteristic current of the towers, grounding, and insulation used on these lines probably is in excess of those occurring in nature. The only flashover experienced on the 220-kv lines occurred in 1933 at a tower having a footing resistance of 25 ohms. This was before the lightning current studies were begun, but the flashover can be accounted for on the basis of the original Lewis and Foust theory by assuming a tower current of 100,000 amperes, a value which has been measured several times in the field.

Table III. Flashovers on Transmission Lines Provided With Preventive Lightning Protection

Line and Tower	Year	Tower Current in Amperes	Tower Footing Resistance in Ohms	Tower Height in Feet	Tower Potential ($I \times R$) (Kv)	Ratio of Tower Potential to Flashover Level
Holtwood-York 63 (66 kv)	1937	58,400	13.8	75	805	0.82
Holtwood-York 145 (66 kv)	1937	60,000	19	76	1140	1.16
Holtwood-Coatesville 40 (66 kv)	1938	64,400	17.2	73	1108	1.30
Holtwood-Coatesville 97 (66 kv)	1939	60,200	5.4	83	325	0.38
Holtwood-Coatesville 99 (66 kv)	1939	13,400	8.5	73	115	0.14
Holtwood-Baltimore 130–56 (66 kv)	1939	62,800	3.6	67	225	0.26
Safe Harbor Perryville 15 (132 kv)	1939	52,600	12.2	137	640	0.41

Table IV. Efficiencies of Preventive Lightning Protection

Line	Years of Study	Lightning Outages*	Recorded Strokes	Efficiency of Protection (Per Cent)
Safe Harbor-Westport-Takoma 220 kv	5	0**	482	100**
Safe Harbor-Riverside 220 kv	2	0	91	100
Safe Harbor-Perryville 132 kv	5	1	249	99.6
Holtwood-York 66 kv	4	2	109	98.2
Holtwood-Coatesville 66 kv				
Before improvements	2†	37	55	33
After improvements	2	3	113	97.4
Holtwood-Baltimore 66 kv				
(Two lines on one right-of-way)	1	1‡	65	98.4

*Single, double, and triple circuit tripouts.

**A flashover of this line occurred in 1933 before the lightning current studies were begun. The estimated efficiency for the entire eight years of operation is:

$$100\left(1-\frac{1}{8/5\times 482}\right)=99.9 \text{ per cent}$$

†Stroke records are complete for only two years (1936 and 1937).

‡Not included is one tripout which occurred before the installation of counterpoise was completed in 1939.

The probable outages for the lines have been recalculated in table VII using the estimated safe characteristic tower currents given above as the maxima that can be carried under any circumstances. The calculations may possibly be further refined in the future when tower and footing impedances become evaluated and their effect in combination with footing resistance is determined quantitatively.

XI. Lightning Arrester Records

Surge-crest ammeter links have been mounted on the lightning arresters at Highlandtown substation in Baltimore since 1935. These arresters are connected to the four 25-cycle, 66-kv circuits of the two Holtwood-Baltimore lines. Each year since their installation, except 1936, they have indicated some current in at least three of the four arrester banks. The maximum current recorded was 2,600 amperes in 1937.

Similarly, arresters connected to other 66-kv circuits have carried small currents from time to time. The largest current recorded was 7,400 amperes in 1939 in the arresters connected to circuit 83 at Violet Hill substation in York. Circuit 83 is an unshielded wood-pole line of the Metropolitan Edison Company connecting through the high-tension bus at the substation to the Holtwood-York 66-kv line.

It is interesting and of some importance to note that during three seasons of study, no indications have been obtained of discharges through any of the four banks of arresters connected to circuits protected by two overhead ground wires and buried counterpoise systems.

XII. Summary

1. Because of the large number of observations, 3,289, which have been made during the six years of study of lightning currents, some confidence can be felt that the data are fairly representative of the several effects of lightning. Some uncertainties still exist in the data, as for instance the effect of tower cross braces on the measurement of tower currents.

2. The distribution curve of the various magnitudes of currents in towers believed

Table V. Efficiencies of Shielding

Type of Line	Years of Record	Number of Strokes	Number of Outages	Estimated Strokes to Conductors	Probable Efficiencies of Shielding Minimum (Per Cent)	Maximum (Per Cent)
220 kv (2 lines) (figure 3)	7*	573	0*	0		
132 kv (figure 4)	5	249	1	0		
	12	822	1	0	99.9	100
66 kv (figure 2) (1 overhead ground wire)						
Strain towers	2	30	1	0	97	100
Suspension towers	2	83	2	1	98	99
66 kv (figure 5) (2 overhead ground wires)	4	109	2	0	98	100

*Includes only years of lightning current study. See table IV.

to have been struck by lightning has been established from 1,201 records. The curve can be used satisfactorily for purposes where the error due to cross braces is not objectionable. Considerable confidence can be placed in the general shape of the curve.

3. Over a period of years it appears that all sections of the transmission lines of the Pennsylvania Water and Power Company are struck by lightning, there being no localities that are immune.

4. The average number of strokes to the transmission lines studied is 126 per 100 miles per year. The actual number of strokes to a given transmission line, however, may vary in the ratio of as much as three to one from year to year. This variation emphasizes the need for examining lightning experience records for a period of several years before any conclusions are reached about lightning phenomena.

5. Analysis of the flashovers which have occurred on lines having overhead ground wires and buried counterpoise systems indicates that flashovers can be caused not only by the ground resistance drop being greater than the insulation strength, but also by the reactive drop due to the rapid rates of current rise which seem to accompany heavy tower currents. On the observed 66-kv lines this latter phenomenon seems to be of critical magnitude when the indicated tower currents have been around 60,000 amperes.

6. Because of this latter phenomenon it appears that no advantage accrues from reducing tower footing resistances on such lines below approximately six ohms. This figure allows for suspected inaccuracies in the measurement of tower lightning currents and footing resistances. It is thought to be desirable that this value of footing resistance be obtained within not more than 200 or 300 feet of the tower base.

7. Operating experience shows that the arrangement of the two overhead ground wires on the newer lines of the company provides practically perfect shielding, that is, probably within less than 0.1 per cent. The experience with a single overhead ground wire is superior to that predicted from laboratory models. The record shows the shielding to be effective for about 98 or 99 per cent of the strokes contacting the Holtwood-Coatesville 66-kv line.

8. Preventive protection embodying the use of overhead ground wires and buried counterpoise installations co-ordinated with line insulation has been shown to be very effective. Since this work has been carried out completely on the 220-kv lines it has been 100 per cent effective. It has been 99.6 per cent effective on the 132-kv line and about 98 per cent effective on the 66-kv lines.

9. Discrepancies were found in the comparison of actual and calculated probable lightning outages. These have been traced to the phenomenon of a maximum surge current which a given construction can apparently withstand irrespective of the measured tower footing resistance.

10. The lightning arresters connected to transmission lines provided with effective preventive protection are seldom called upon to carry lightning discharges, and then they are apparently of small magnitudes.

Table VI. Comparison of Actual and Probable Outages

Probable Outages Calculated on Basis of Lewis and Foust Theory as Originally Presented[7]

Line	Years of Record	Lightning Outages Per Year Actual	Probable
Safe Harbor-Westport-Takoma 220 kv	8	0.13	0.014
Safe Harbor-Riverside 220 kv	2	0	0*
Safe Harbor-Perryville 132 kv	5	0.2	0.0078
Holtwood-York 66 kv	4	0.5	0.29
Holtwood - Coatesville 66 kv	2	1.5	0.68
Holtwood - Baltimore 66 kv (Two lines on one right-of-way)	1	1	0.2

* Does not include section 1.03 miles in length where there are no overhead ground wires.

Table VII. Comparison of Probable and Actual Outages

Probable Outages Calculated on Basis of the Suggested Modification of the Lewis and Foust Theory

Line	Estimated Safe Maximum Current	Lightning Outages Per Year Actual	Probable
Safe Harbor-Westport-Takoma 220 kv	Greater than 150,000 A	0.13	0.014
Safe Harbor-Riverside 220 kv	Greater than 150,000 A	0	0*
Safe Harbor-Perryville 132 kv	90,000 A	0.2	0.05
Holtwood-York 66 kv	60,000 A	0.5	0.58
Holtwood-Coatesville 66 kv	60,000 A	1.5	1.3**
Holtwood-Baltimore 66 kv (Two lines on one right-of-way)	60,000 A	1	1

*Does not include 1.03 miles section where there are no overhead ground wires.
**Includes allowance for shielding being only 99 per cent efficient. (See section IX.)

References

1. Safe Harbor-Westport 230 Kv Transmission Line, **Edwin Hansson.** Electrical Engineering, volume 51, December 1932, pages 834–8.

2. Direct Measurement of Surge Currents, **C. M. Foust** and **J. T. Henderson.** AIEE Transactions, volume 54, 1935 (April section), pages 373–8.

3. Lightning Investigation on a 220-Kv System—III, **Edgar Bell.** AIEE Transactions, volume 59, 1940, pages 822–8.

4. Lightning Investigation on Transmission Lines—VII, **W. W. Lewis** and **C. M. Foust.** AIEE Transactions, volume 59, 1940 (April section), pages 227–32.

5. Theory and Tests of the Counterpoise, **L. V. Bewley.** AIEE Transactions, volume 53, 1934 (August section), pages 1163–72.

6. Shielding of Transmission Lines, **C. F. Wagner, G. D. McCann,** and **G. L. MacLane, Jr.** AIEE Transactions, volume 60, 1941.

7. Lightning Investigation on Transmission Lines—IV, **W. W. Lewis** and **C. M. Foust.** Electrical Engineering, volume 53, 1934 (August section), pages 1180–6.

8. Probable Outages of Shielded Transmission Lines, **S. K. Waldorf.** AIEE Transactions, volume 56, 1937 (May section), pages 597–600.

High-Voltage Bushings Designed to Meet Modern Service

T. F. BRANDT
MEMBER AIEE

H. L. RORDEN
MEMBER AIEE

Introduction

BUSHINGS are a very important part of over-all system insulation. Since all of the power transmitted from station to station and station to consumer passes through a great many bushings the majority of which are a part of vital equipment such as transformers, breakers, etc., it is immediately apparent that system-service continuity depends, to a large degree, upon satisfactory bushing operation. Early bushing designers were handicapped by a lack of operating history and high-voltage testing facilities. However, in spite of these handicaps they developed some sound designs as evidenced by the many 25- to 30-year-old bushings in satisfactory service today. In these early bushings porcelain was one of the principal dielectrics.

Comprehensive studies of porcelain oil-filled bushings have been made to improve both the electrical and mechanical characteristics. As a result of these studies a better understanding of the internal and external electrostatic field conditions has resulted, and a new method of voltage grading developed. Mechanical improvements have been made which not only simplify construction, but stabilize the electrical characteristics by maintaining the over-all assembly close to its original condition. These developments will be discussed here.

Control of Electrical Characteristics in Bushing Design

Design Requirements

From an electrical standpoint, a bushing must have adequate internal insulation to provide a safe margin between internal puncture and external flashover. There also should be no corona formation at operating voltage and radio interference must be kept at a minimum. The over-all electrical characteristics of a bushing should be stabilized in so far as they affect operating performance. A design which has excellent electrical characteristics in the laboratory, but is subject to change under operating conditions, is undesirable if these changes adversely affect the performance. Extensive tests have been made in the laboratory and operating records have been carefully checked to guard against this possibility.

A bushing must provide sufficient insulation in two ways. First, it must have the required external flashover voltage commensurate with its rating and the insulation level of associated equipment, and secondly, the internal puncture strength must have a satisfactory margin over the external flashover. Since external flashover of a bushing is through a surrounding medium, such as the air around the upper or weather end, full consideration must be given the characteristics of this medium to obtain the balanced design necessary for stable electrical performance.

Porcelain oil-filled bushings use insulating materials of differing dielectric constants or flux-carrying capacities. With insulation in series there is a tendency for those of lower dielectric constants to have imposed relatively greater portions of the total voltage. Accordingly, it is essential that high localized stress be avoided in those insulating zones having low dielectric constants. This applies to the medium surrounding the bushing, as well as the insulation within it.

Means of Controlling Characteristics

In order to determine the effectiveness of voltage grading or electrostatic field-controlling arrangements a series of impulse and 60-cycle studies were made. Many assemblies were tested, but only representative types having practically the same striking distance will be discussed here. These are shown in figure 1.

In figure 2 are shown photographs of corona due to 60-cycle overstress on the assemblies of figure 1. Figure 3 shows photographs of the field patterns around these same assemblies as indicated by corona from impulse-suppressed discharges. Complete electrical data on the above assemblies, along with voltages applied in the various photographs, are given in table I.

In figure 1*a* is shown a porcelain tube with a metal cap and flange, but *without* a central conductor. Appreciable 60-cycle corona can be seen at the cap in figure 2*a*, while a uniform field pattern exists in figure 3*a* for both polarities. This assembly is included to show the radical change in the field when a conductor is passed through the center of the tube. Figure 1*b* is the same as figure 1*a* except *with* a central conductor added. Heavy 60-cycle overstress is apparent in figure 2*b* immediately above the metal flange and figure 3*b* shows the field overstress due to suppressed discharges.

The difference between the positive and negative field patterns of figure 3 is in accord with observations made on the study of dielectric fields existing between various types of electrodes in air.[1] It is possible to control these stresses to some degree by the shape and arrangement of electrodes and by various methods of grading. The central conductor of figure 1*b* has changed the electrostatic field so that the air at the edge of the flange is highly overstressed. This overstress is due to the low dielectric constant or flux-carrying capacity of air as compared to porcelain. The air space between the central conductor and the porcelain is subject to overstress for the same reason. These two regions are the cause of unstable flashover and radio-interference characteristics in this type of bushing.

In contrast with figure 2*a* there is no overstress at the cap in figure 2*b*. The central conductor shields the cap since most of the electrostatic flux lines emanating from the flange terminate on the central conductor well below the cap. Figure 4 shows the approximate field condition for figure 1*b*. Initial overstress starts in the air immediately above the flange at *A*. As the voltage is increased, the air becomes ionized, forming a conducting envelope over the porcelain surface to a point where flashover occurs at a rather low voltage.

In figure 1*c* is illustrated a typical solid porcelain bushing. Figures 2*c* and 3*c* show its 60-cycle and impulse corona patterns, which are similar to those of figures 2*b* and 3*b*. The performance of the figure 1*c* design can be improved somewhat by changing the porcelain configuration.

Oil-filled bushing designs readily adapt themselves to the elimination of localized overstress. For example figure 1*d* is a

Paper 41-66, recommended by the AIEE committee on protective devices, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 1, 1940; made available for preprinting December 18, 1940.

T. F. Brandt and H. L. Rorden are development engineers for the Ohio Brass Company, Barberton, Ohio.

1. For numbered reference, see end of paper.

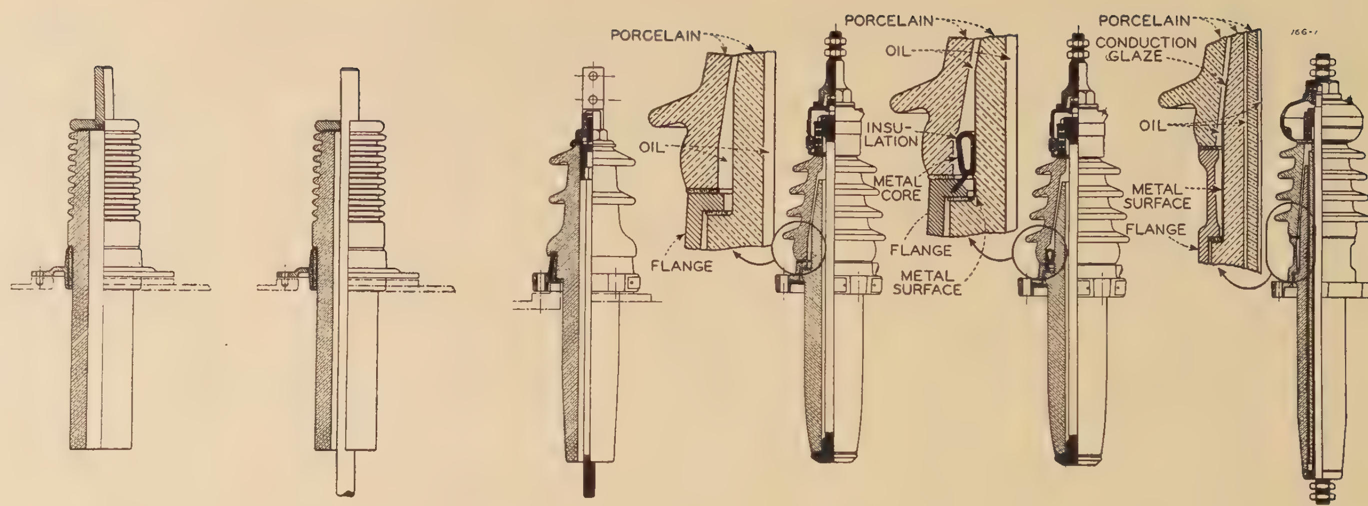


Figure 1. Details of bushing construction

Figure 2. Corona due to 60-cycle over-stress

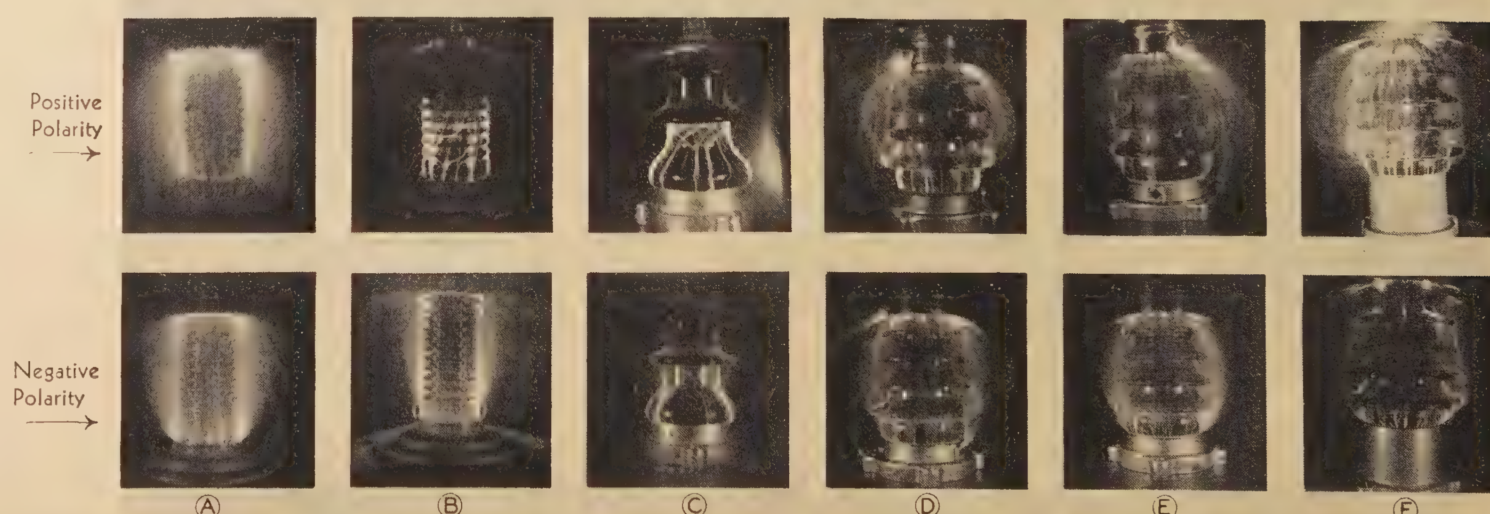


Figure 3. Corona due to suppressed impulse discharge

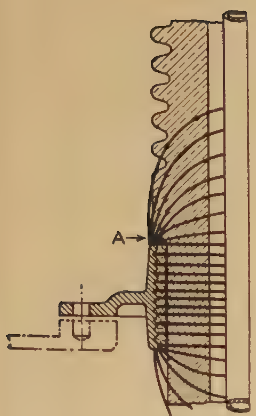


Figure 4. Field pattern for figure 1b

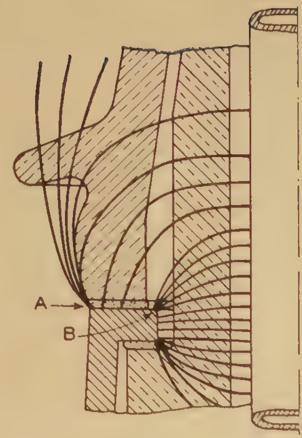


Figure 5. Field pattern for figure 1d

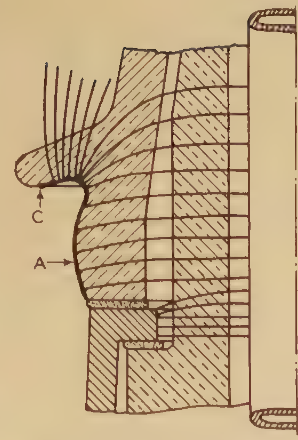


Figure 6. Field pattern for figure 1d near flashover

simple oil-filled assembly with no grading means other than its porcelain configuration. The 60-cycle corona in figure 2*d* shows the heavy overstress immediately above the flange. The approximate field condition around the flange area of the figure 1*d* design below the point of excessive corona is shown by figure 5. The inside air between the conductor and the porcelain has been replaced by a combination of oil and wrapped insulation, thereby preventing overstress in this area. However, no effort has been made to control the field at the mounting flange, thereby resulting in two highly stressed regions. One is at *B*, figure 5, inside the bushing where the flange terminates in the oil; the other is at *A*, the outer exposed edge of the flange. The voltage gradient at *B* is higher than at *A*. However, since the dielectric strength of the oil at *B* is appreciably higher than that of the air at *A*, overstress appears first at *A* at a lower voltage gradient.

This overstressing at *A* establishes a conducting envelope of ionized air with increasing voltage. It does not progress up the bushing as far as on figure 2*b* but stops under the first petticoat. This is due to the conducting envelope assuming a form of grading means, as shown by figure 6. This same condition is shown in figure 2*c* where overstress stopped abruptly under the porcelain petticoat. This has not been generally appreciated and many bushings have been made in both the solid and oil-filled types with the region from *A* to *C*, figure 6, unstable, thereby involving possible radio interference.

Figure 1*e* is similar to figure 1*d* except that a capacity grading means in the form of an insulation-wrapped metal core is incorporated. The metal core and the metalizing on the porcelain tube are electrically connected to the flange. Since the wrapped metal core extends up inside the bushing, it partially shields the outside exposed edge of the mounting flange. At the same time it reduces the voltage stress in the oil at the inside edge of the flange and at the top edge of the metalizing on the porcelain tube. Covering the metal with insulation is essential for proper field control. Tests on various forms of uninsulated metal grading means have proved them to be relatively ineffective.

The approximate field condition of figure 1*e* is shown by figure 7. The metalized, ground potential surface on the porcelain shorts out the highly stressed oil at *B* in figure 5. The point *A* is not completely shielded since it goes into corona as shown by figure 2*e*. However, the corona is materially reduced from that shown on figure 2*d*. In table I, figures 1*d* and 1*e* are seen to have practically the same 60-cycle flashover although an appreciable difference exists in the radio-interference values. This is because at flashover voltage the external field control set up by the conducting envelope of corona in figure 2*d* and the grading means of figure 2*e* are equally effective in so far as flashover voltage is concerned.

In the lower operating voltage bushings, namely 69 kv and below, cover opening diameters have been somewhat restricted. The problem here has been to develop the most efficient methods of using the available space. Various voltage grading arrangements have been used, but most of them require space which can be used better for effective insulation between the central conductor and ground. A newly developed method, not requiring this, is a form of resistance grading by means of conduction glaze applied directly to the porcelain surface. Figure 8 shows the approximate field of the figure 1*f* design which utilizes this resistance grading.

Figure 7, the type used in figure 1*e*, can be called an auxiliary means since it is not integral with the porcelain. Figure 9 is an effective field-controlling arrangement used on present high-voltage bushing designs of ratings, 92 kv and above. This type, formed integral with the porcelain, is very effective where space permits its use. The types in figures 7 and 9 function by means of their configuration and the voltage drop through a dielectric. Figure 8 functions because of the voltage drop through a high resistance. There must be enough voltage drop along the conduction-glazed surface from *D* to *E* to prevent overstressing at both *D*, the

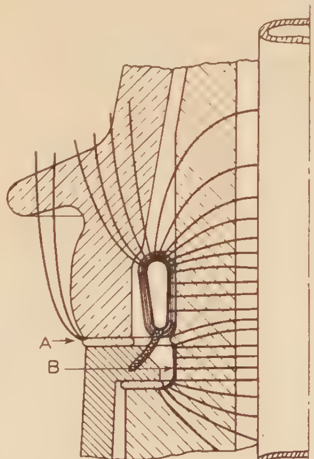


Figure 7. Field pattern for figure 1e

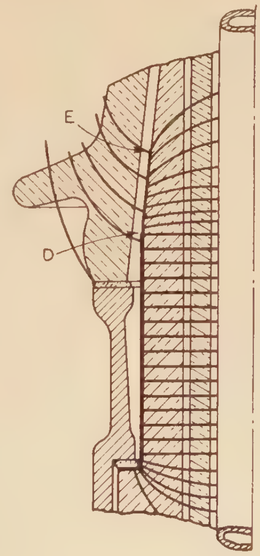


Figure 8. Field pattern for figure 1f

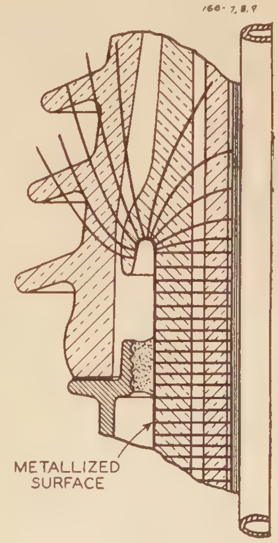


Figure 9. Field pattern for figure 11

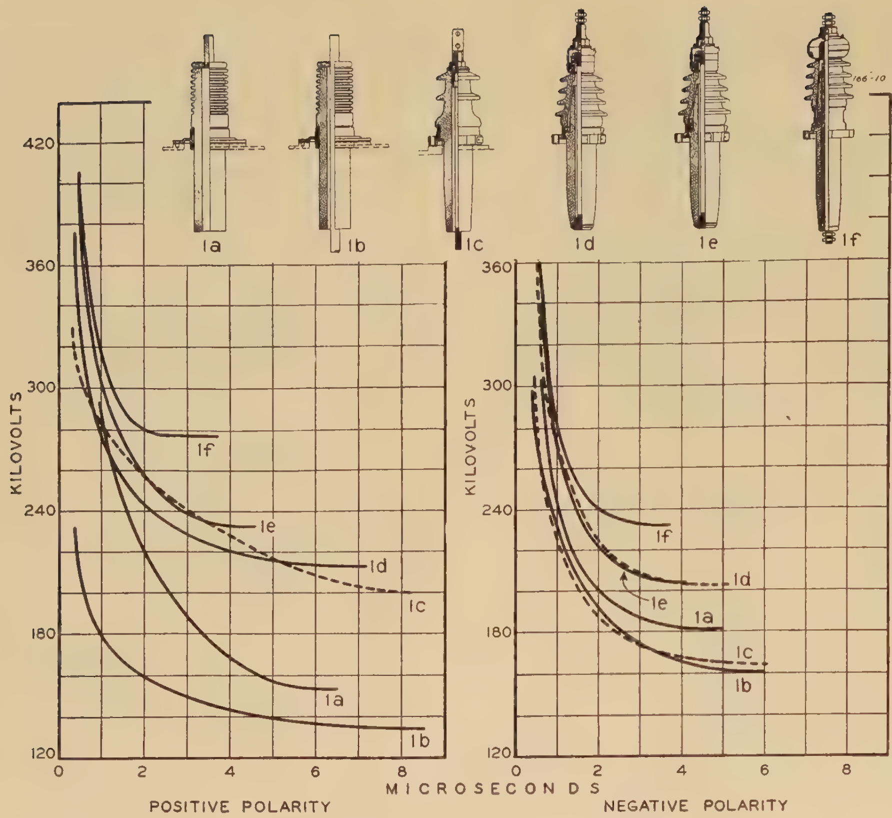


Figure 10. Volt-time characteristics of assemblies in figure 1

end of the metalizing, and at E. This means that the resistance of the conduction glaze region from D to E must be maintained within definite limits by careful manufacturing control. Likewise, the conduction glaze must have permanently stable characteristics.

Figure 1*f* illustrates a modern bushing using resistance grading. Figure 2*f* shows a very light glow between the petticoats with 120 kv, 60 cycle applied on the bushing. This shows the absence of localized overstress outside the bushing. The radio interference (table I) indicates the absence of the internal overstress. Figure 8 shows the field condition discussed in the previous paragraph. This construction improves the electrical characteristics materially by approaching the uniform field of a sphere gap rather than the concentrated field of a rod gap. This is particularly emphasized by the curves in figure 10 where this design is seen to have a rather high and flat volt-time characteristic. The other extreme is the design of figure 2*b* whose poor field condition results in the lowest volt-time curve of figure 10.

Bushings rated 92 kv and above have received the same study, and figure 11 is the one developed for 115-kv service. It is provided with capacitance grading of the type shown in figure 9, and gives proportionately the same performance as figure 1*f*. Since these modern designs are stable at voltages considerably in excess of their rating, it is safe to assume that their characteristics will remain unchanged under normal operating conditions.

Mechanical Improvements

Excellent electrical properties are of little value if the mechanical design does not maintain the bushing at or near its original condition for a long period of time. This requires, primarily, sturdy construction with efficient gasket joints and one that will maintain a stable condition of the oil. Figure 11 shows a modern bushing having these characteristics.

An early design is shown by figure 12 where all of the external parts of the bushing were completely cemented together. If gasket leaks or other mechanical troubles developed, there arose a difficult maintenance problem.

A later design, shown in figure 13, could be more easily maintained since the gasket joints could be tightened or readily replaced. However, the large metal parts cemented to porcelain presented occasional problems. In the first place there was the possible chance of a cement change with time where joint A, figure 13, was directly exposed to the weather. Weatherproof coatings have been used to prevent cement deterioration, but under extreme conditions they have been found

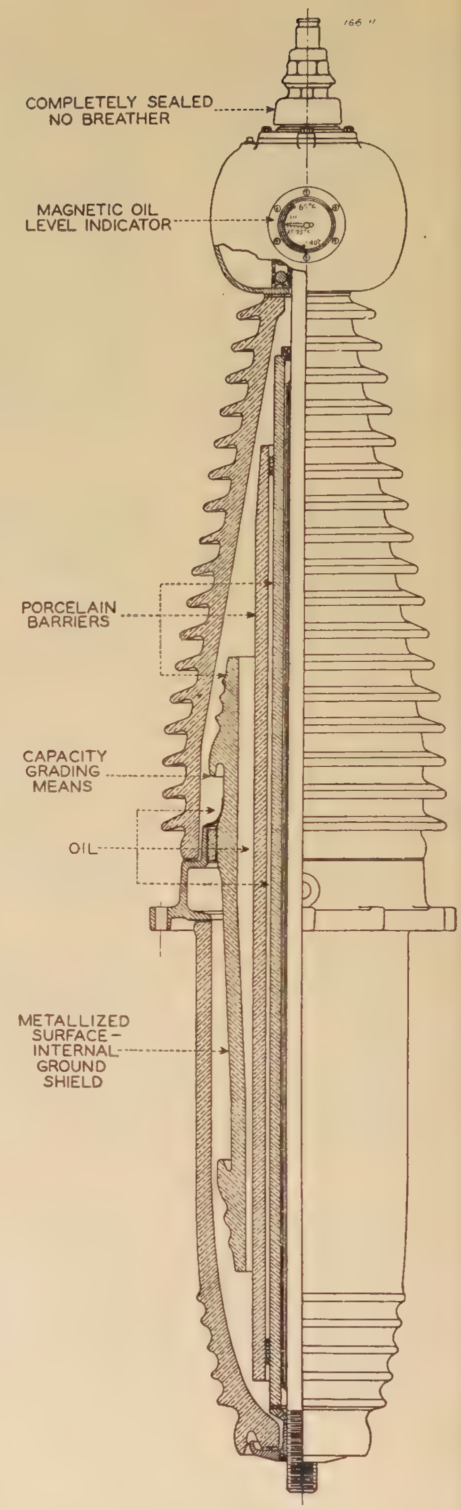


Figure 11. Present design, high-voltage porcelain oil-filled bushing

wanting. Also a differential thermal expansion existed between the metals and porcelain. Special treatment of the cement joints to compensate for thermal expansion has also been tried. There are many thousands of large oil-filled bushings such as those of figures 12 and 13 in service which have given a good account of themselves, but gasket leaks and damaged porcelain are not uncommon.

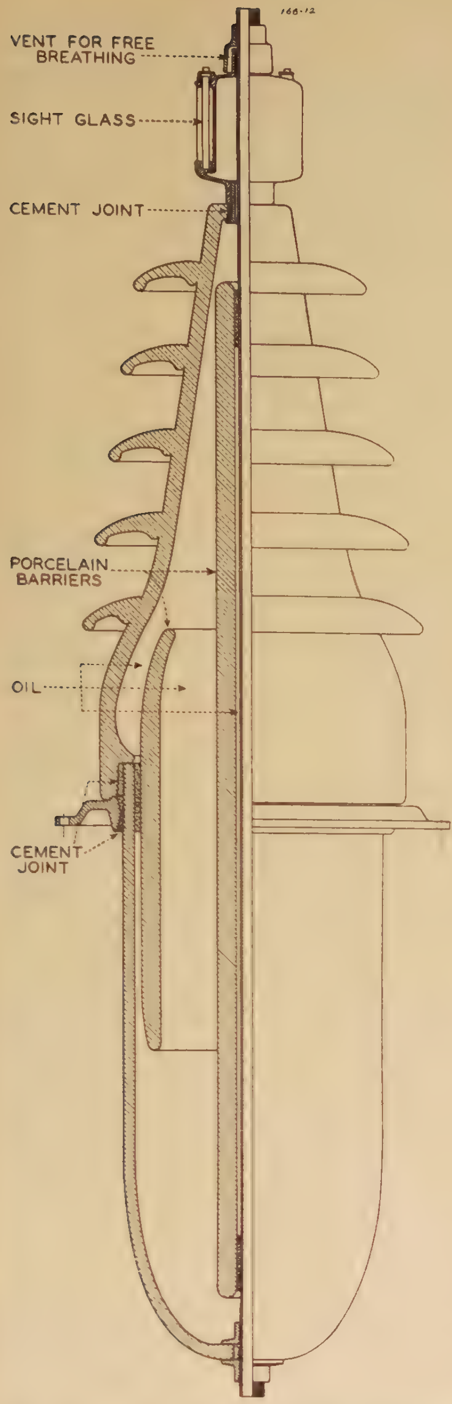


Figure 12. High-voltage porcelain oil-filled bushing of early design (1920)

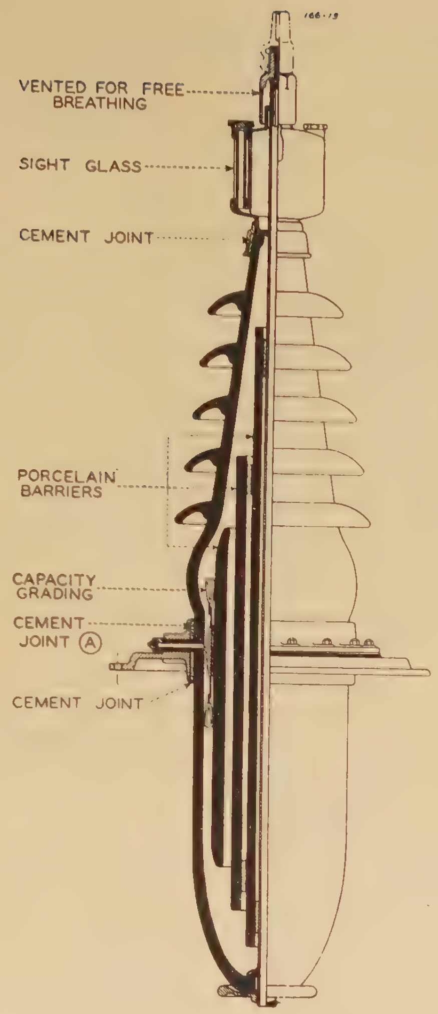


Figure 13. High-voltage porcelain oil-filled bushing of ten years ago

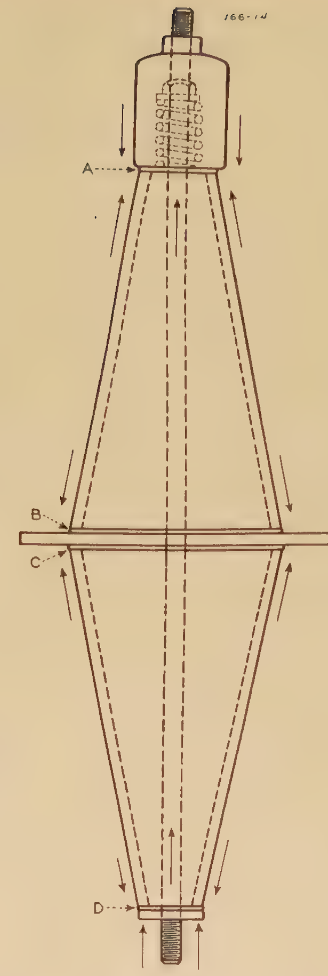


Figure 14. Schematic view of compression assembly showing how gaskets are kept under compression

Several years ago the full compression-assembled bushing was introduced. This produced a very rugged assembly, eliminated external cement joints, and kept the gasket joints permanently oil-tight. It is a well-established fact that most gasket materials kept under constant pressure between mating surfaces remain oil-tight indefinitely. Formerly, gaskets had to keep themselves tight. To illustrate this, when the gaskets in bushings such as figure 13 were originally tightened, the material, due to its initial resilience, exerted a strong back pressure against the mating surfaces. However, this back pressure for practically all gasket materials diminishes with time. In addition some shrink or take a permanent set. In any event, in a relatively short time the gasket joint is not as effective as when first made.

The full-compression assembly shown

Table I

Assembly Figure Number	Corona Due to 60-Cycle Overstress: Kv (RMS) on Assembly	Corona Due to 60-Cycle Overstress: Photo Figure Number	Corona Due to Impulse Suppressed Discharge: Kv (Crest) on Assembly*	Corona Due to Impulse Suppressed Discharge: Photo Figure Number	60-Cycle Flashover (Kv RMS): Dry	60-Cycle Flashover (Kv RMS): Wet	Critical Flashover $1^1/_2$ x 40-Microsecond Wave Kv (Crest): Pos.	Critical Flashover $1^1/_2$ x 40-Microsecond Wave Kv (Crest): Neg.	Radio Interference Voltage on Bushing for 100-Microvolt Level Kv (60 Cycle RMS)
1a	89	2a	377	3a	91	72	153	182	41.2
1b	75	2b	205	3b	77	65	133	161	20.1
1c	81	2c	315	3c	95	74	202	165	21.2
1d	81	2d	350	3d	115	78	211	204	21.2
1e	81	2e	350	3e	119	88	234	206	44.7
1f	118	2f	422	3f	131	93	276	233	118.0

*Wave is "chopped" by parallel rod gap, allowing voltage considerably above critical flashover value.

Surges on Chicago 12-Kv System

F. O. WOLLASTON
ASSOCIATE AIEE

H. J. PLUMLEY
ASSOCIATE AIEE

VOLTAGE surges on the 12-kv system of Commonwealth Edison Company have been recorded and studied for 20 years. This paper presents the Chicago data and outlines a theory for the explanation of system overvoltages that is in good agreement with the observations.

A geographical layout of the 12-kv system is shown in figure 1. At present there are six separate zones consisting of a station bus and its associated radial 12-kv lines. Each zone has about 50 or 60 lines averaging about three miles long. All lines are underground cable except in the Calumet zone where there are some sections of overhead line. New zones have been added from time to time through the period of this study. Prior to 1928 the four zones then existing were directly connected through 12-kv tie lines. These ties were subsequently removed and since 1928 the only interconnections have been indirect through the 66-kv system.

Figure 2 is a schematic one-line diagram of a typical bus layout for any one of the six generating or distributing stations in Chicago. The two basic features of every 12-kv zone in the system are (1) independent feed of bulk power from each of the two independent 66-kv systems and (2) provision for splitting the local 12-kv system into two independent systems by the operation of sectionalizing breakers. Two types of grounding are used in the zones involved in the surge studies. In one type a derived neutral transformer having an inductive impedance of three ohms is used. In the other type, one generator neutral is grounded through three ohms of resistance.

Spark-gap installations have been maintained on the system since 1919. The present locations are indicated in figure 1. The device is shown schematically in figure 3. A sphere gap in series with a fuse, a protecting resistor, and a recorder is connected between each phase of a 12-kv substation bus and ground. The surge of current caused by a gap flashover operates a simple solenoid connected to the pen of the clock-driven recorder, leaving a jog on the chart which shows when the overvoltage occurred and which phase it was on. The magnitude of the overvoltage remains unknown, except that the breakdown of the gap establishes its lower limit. The gap settings have been adjusted from time to time through the 20 years of the study to cover the range 1.85 times normal crest voltage to 3.5 times normal crest voltage. As the gap settings were increased there was a corresponding decrease in the number of overvoltages recorded, until at 3.5 times normal crest voltage no records were obtained. The time of occurrence of each spark-gap operation is carefully correlated with the daily log of switching operations and the oscillograph records of abnormal conditions in the system.

The oscillograph records provide another distinct line of attack on overvoltage phenomena by facilitating the study of simultaneous or "sympathetic" failures. Such occurrences consist of a failure in one part of the system, followed almost immediately by one or more failures elsewhere in the same system, perhaps several miles distant from the original failure. The original failure is referred to throughout this paper as the primary failure while the one or more failures that may occur almost simultaneously are referred to as secondary failures. The terms primary and secondary as used here should not be confused with the same terms used to designate two transformer-coupled circuits. Questions that naturally arise are: (*a*) Is the secondary failure caused by a brief transient or by the increase in 60-cycle voltage on two phases incidental to the grounding of the faulted phase? (*b*) If transients are present, what is their nature? (*c*) Are the secondary failures associated with the switching that clears the original failure, or do they precede such switching? The routine high-speed records, supplemented by staged tests, have assisted in elucidating these matters.

General Conclusions

From the studies of records of over 700 spark-gap operations, 54 simultaneous failures of lines or apparatus in service, and 15 staged tests in which faults were thrown on the system, the following conclusions have been drawn:

1. The maximum magnitude of overvoltages on this system is about 3.5 times normal crest voltage.

2. The overvoltages of highest magnitude are associated with system failures and are best understood by use of the "cancellation-wave" theory; the highest transients occur at the inception of the fault, not during the switching that clears the fault.

3. Overvoltages associated with routine switching are amenable to the "cancellation-wave" theory, but are usually of smaller magnitude than those associated with failures and are therefore of less interest.

4. Most secondary failures in simultaneous failures are caused by the overvoltages mentioned in conclusion 2.

Paper 41-51, recommended by the AIEE committees on power transmission and distribution and protective devices, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 25, 1940; made available for preprinting December 12, 1940.

F. O. Wollaston is supervising research engineer and H. J. Plumley assistant research engineer for the Commonwealth Edison Company, Chicago, Ill.

---

in figure 11 compensates for all gasket variations since the mating parts are continually acted upon by the compression spring in the oil reservoir. This is shown schematically in figure 14 which indicates how the compression loading of the spring is transmitted to the various gasket surfaces at *A*, *B*, *C*, and *D*. The compression spring must have adequate "pickup" or deflection so that any shrinkage of the gaskets will not release the spring enough to affect its loading appreciably.

With dependable gasket joints now available, it is possible to have a completely sealed bushing. This has been done over an entire range of oil-filled porcelain bushings to secure a stable oil condition. Moisture, oxygen, and sunlight are all detrimental to insulating oil, but by completely isolating the oil from them, its dielectric properties remain practically constant. Where it is desired to check the oil level occasionally, especially in the larger bushings, a magnetic oil level indicator is used. This affords a definite indicating means without exposing the bushing oil to sunlight, moisture laden air, etc.

In order to keep the pressure in the bushing within reasonable limits, adequate space in the top oil reservoir shown must be provided for oil expansion due to temperature changes. The compression spring arrangement must be adequate to keep the gasket joints tight against the various pressures in the bushing.

Reference

1. The Control Gap for Lightning Protection, Ralph Higgins and H. L. Rorden. AIEE Transactions, volume 55, 1936 (September section), pages 1029–34.

5. The overvoltages on the Chicago 12-kv system are essentially power-frequency phenomena.

6. When an overvoltage condition is set up, it is propagated throughout all parts of the system that have direct metallic connections, but is strictly confined to such metallically connected parts.

7. Secondary failures occur only in insulation that is deteriorated to the point where it will not withstand (*a*) 60-cycle overvoltage of value 1.73 times normal crest to ground applied for the duration of a system fault to ground, (*b*) a few cycles of transient overvoltage having a maximum magnitude of 3.5 times normal crest to ground.

8. Zones having a derived neutral ground, which is essentially inductive, have more and higher transient overvoltages than zones having the generator neutral grounded through resistance.

9. The number and magnitude of overvoltages recorded in the zone having some sections of 12-kv overhead line, excluding overvoltages due to lightning and unknown causes, were about the same as for the zones in which all the lines were underground.

Spark-Gap Data

The data on system overvoltages obtained in the period 1919–28, when all the 12-kv zones were directly interconnected, are shown in figure 4. A few surges exceeded 3.2 times normal, which was the highest gap setting used in this period. The recording devices were needle gaps. Similar data for sphere gaps (one-inch spheres) are given in figure 5 for the period 1932–38, when the zones were not directly interconnected. A few overvoltages exceeded three times normal, but none exceeded 3.5 times normal. The latter setting was maintained at all spark-gap installations for about $1^1/_2$ years. From this it appears that the maximum overvoltages on the system do not exceed 3.5 times normal. The needle-gap and sphere-gap data both show that overvoltages associated with failures are usually higher than overvoltages associated with routine switching.

The correlation of overvoltages with failures is shown in figure 6. About 40 per cent of all faults are accompanied by overvoltages of twice normal or greater. Only about six per cent of the faults are accompanied by overvoltages exceeding three times normal.

Comparing figures 4 and 5, it is seen that more overvoltages of a given magnitude occurred during 1919–28, when needle gaps were used, than during 1932–38, when sphere gaps were used. The reasons are threefold:

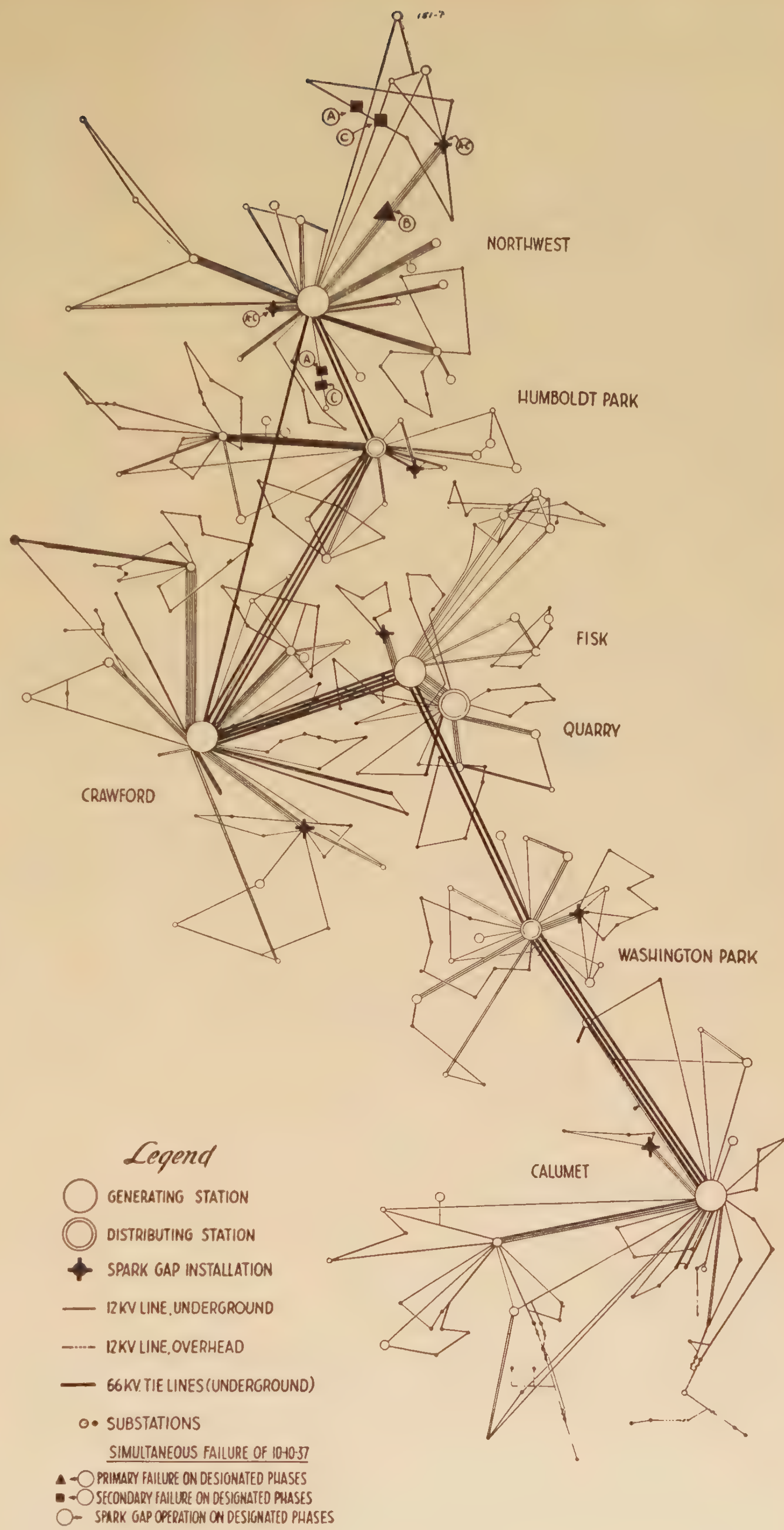


Figure 1. Chicago 12-kv system

(*a*). The zones were directly interconnected in 1919–28, so that a system disturbance might leave a record at every spark-gap installation, instead of at only one or two as was the case for 1932–38.

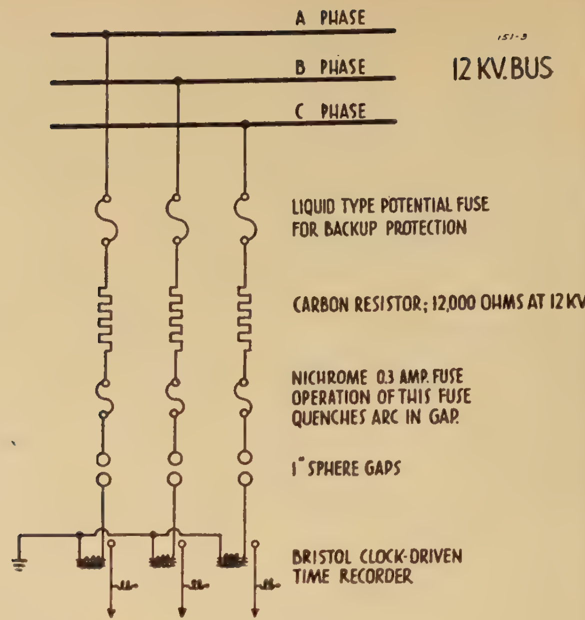
(*b*). There were many more failures, hence many more chances of having system overvoltages, in the 1919–28 period than in 1932–38.

(*c*). Needle-gaps have a greater tendency than sphere gaps to flash over at less than the nominal setting as a result of ionization and accumulation of dust in the gap.

It may also be inferred from these facts that the overvoltages were not high-frequency phenomena, since the time lag of the needle gaps apparently did not suppress them appreciably. More reliable evidence to prove the point is presented later in the paper.

Concerning the accuracy of the surge-recording devices used in the study, it is thought that sphere gaps are very reliable, needle gaps somewhat less so, and klydonographs rather inaccurate. Capacity-coupled klydonographs were tried for about a year, but the records were found to be worthless. The klydonographs were connected in parallel with the needle gaps. Comparison of the magnitudes indicated by the two methods for each recorded surge showed that the klydonograph installations were not reliable.

Figure 3. Spark-gap surge recorder



Simultaneous Failures

From the standpoint of the operating engineer, surge phenomena are of practical importance principally because of the electrical failures of lines and equipment that are caused by them. The occurrence of simultaneous failures is the most common manifestation of troubles caused by surge voltages. During the period 1923–39, there were 54 sets of simultaneous failures on the Chicago 12-kv systems. Forty-nine were double failures, each involving one primary and one secondary failure, while five were triple failures, each involving one primary and two secondary failures. With one exception, every set of simultaneous failures involved a line. Apparatus failures that were involved include three generator armatures, four transformers, three reactors, three oil switches, and two bus structures.

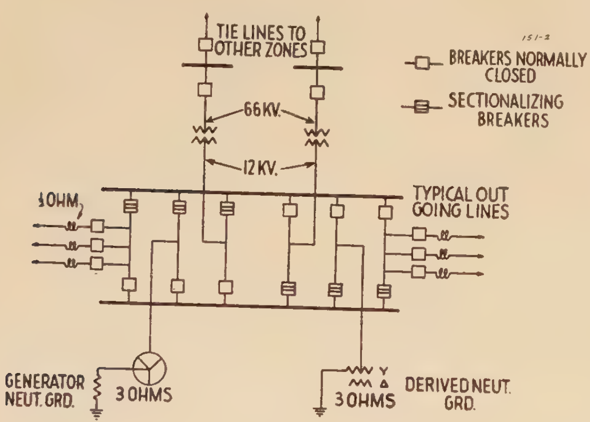


Figure 2. 12-kv station bus diagram

During the period under consideration there were 1,240 primary failures on the Chicago 12-kv systems. Of these failures, 4.35 per cent caused simultaneous failures to occur, thus increasing the total number of 12-kv system failures by 4.84 per cent.

An especially interesting group of simultaneous failures, which occurred in the Northwest zone, is illustrated on figure 1. The primary failure, which was in all probability B phase at the location indicated, originated a transient overvoltage on A and C phases that caused four distinct additional failures and left a record on A and C phases at both of the spark-gap installations in the Northwest zone. The gaps were set at three times normal voltage. This case nicely illustrates the fact that surges are confined to those parts of the system that are metallically connected to the point of surge origin.

Simultaneous failures may be divided into four types based on the time lag existing between the inception of the primary and secondary failure. These are:

1. Secondary failure occurs within one or two cycles of the primary failure's inception, i.e., simultaneous with the initial surge caused by the primary failure.

2. Secondary failure occurs during the steady-state fault period of the primary failure.

3. Secondary failure occurs simultaneous with the clearing of the primary failure.

4. Secondary failure occurs a definite length of time after the clearing of the primary failure.

No oscillograph records of type 3 failures have been obtained in Chicago. It is reasonable to assume, however, that such failures are possible, and so this type has been included. Most simultaneous failures appear to be of type 1. This is inferred from the fact that the oscillograph records usually show both failures existing at the start of the record, the start being about 0.1 second (six cycles) after the inception of the primary failure. Many records of this type have been obtained. Type 2 failures are fairly common, while type 4 failures are rather rare. Type 2 is illustrated by the oscillogram in figure 7. On this record, a B-phase-to-ground cable fault, located three miles from the station, existed from P to Q. B-phase voltage is depressed while A and C voltages are above normal. At Q the secondary fault occurred on C phase to ground in another cable one-fourth mile from the station. For three cycles, Q to R, both faults existed simultaneously. At R, the primary fault cleared, leaving the C-phase fault on the system. A few records of type 4 simultaneous failures have been obtained on the 12-kv system, but unfortunately these records are not suitable for reproduction. An entirely similar case is, however, available from the records of the 9-kv 25-cycle system and is shown in figure 8. The primary fault was on A phase, S to T. This fault cleared at T and the system was normal

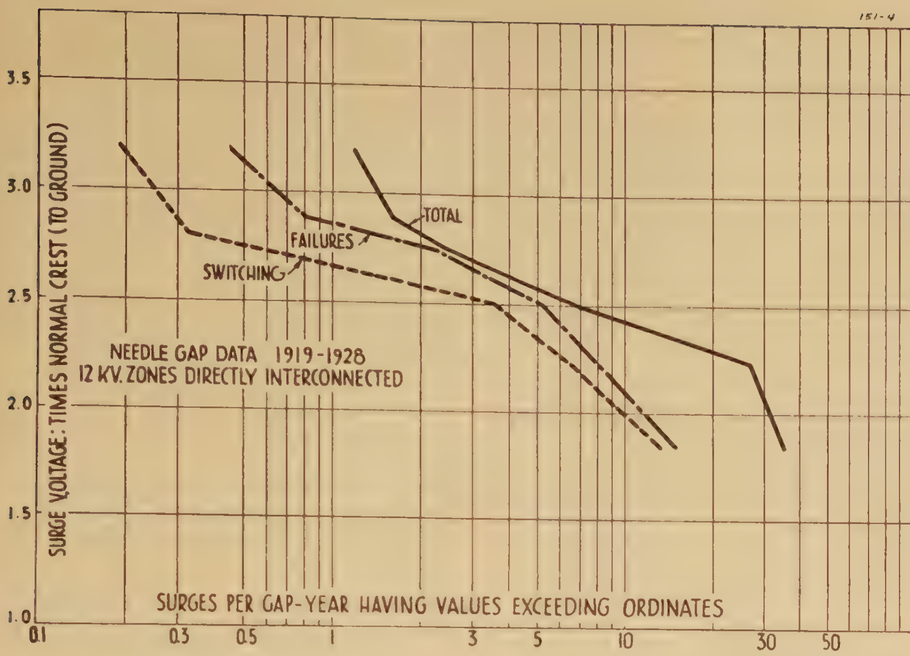


Figure 4. Surge data for 12-kv system, 1919–28

for 1.6 seconds, T to U. At U, the secondary fault occurred on B phase to ground, continuing to V, at which point it was cleared from the system. This interesting record clearly shows that a very definite time lag may occur between the period during which insulation is overstressed and the actual time of its electrical breakdown.

Staged Tests

It is easier to grasp the significance of the test data if the postulated theory of surge production is first understood. The discussion will be confined to surges caused by single line-to-ground faults, which are the highest occurring on the Chicago 12-kv system. The overvoltage resulting from the fault may properly be considered in three parts, as follows.

A. The "Make" Transient

If the initiation of the fault is a simple "make" operation involving no intermittent arcing, then on the approximation that all circuit elements are linear the effect is precisely as though the fault were replaced by a single-phase voltage generator of zero impedance, generating a cancellation voltage that is at all times exactly equal and opposite to the unfaulted steady-state voltage at the fault. The actual voltages and currents in all parts of the network may be obtained by superposing on the unfaulted steady-state condition the transient and ensuring steady state of the network as fed by the cancellation generator.

Figure 9 shows a schematic three-phase diagram of the 12-kv system at a generating station. There are n outgoing lines, each equipped with one-half-ohm reactors. The simplification of zero interphase coupling is introduced and the n conductors and reactors on each phase are grouped to give single parallel equivalents.

A fault is applied on C phase of one of the lines. The cancellation voltage, which may be thought of as a traveling wave if the fault is fairly remote from the station, travels into the station, where it initiates a complex transient whose frequencies are determined mainly by the inductance of the faulted line's reactor and the total system capacitance to ground. Let E be the normal phase-to-ground peak voltage. The theoretical limiting value for the cancellation transient at the bus, assuming infinite neutral impedance, is $4E$ if there are no outgoing lines other than the faulted line, and $2E$ if there are a large number of outgoing lines. This latter value is reduced slightly by the presence of a neutral grounding impedance of a few ohms, the reduction being greater with a resistance ground than with an inductance ground. In any case, the transient resulting from the incoming wave appears almost symmetrically on all three phases of the system. The resulting system overvoltage is the superposition of this cancellation wave and the normal steady state. It is reasonable to expect that for the Chicago

Figure 5. Surge data for 12-kv system, 1932–38

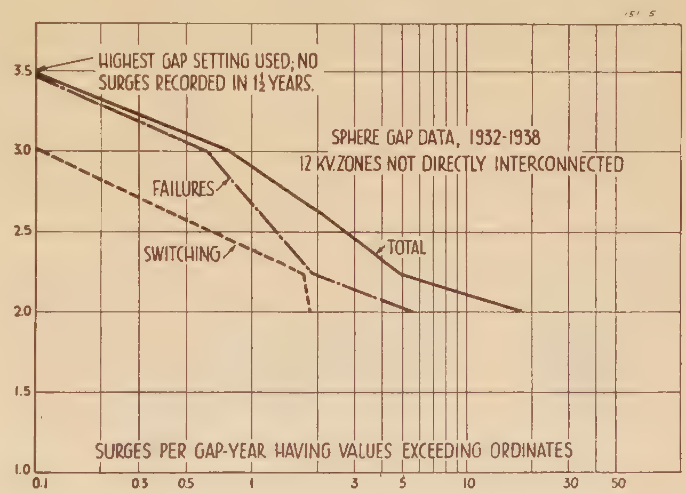
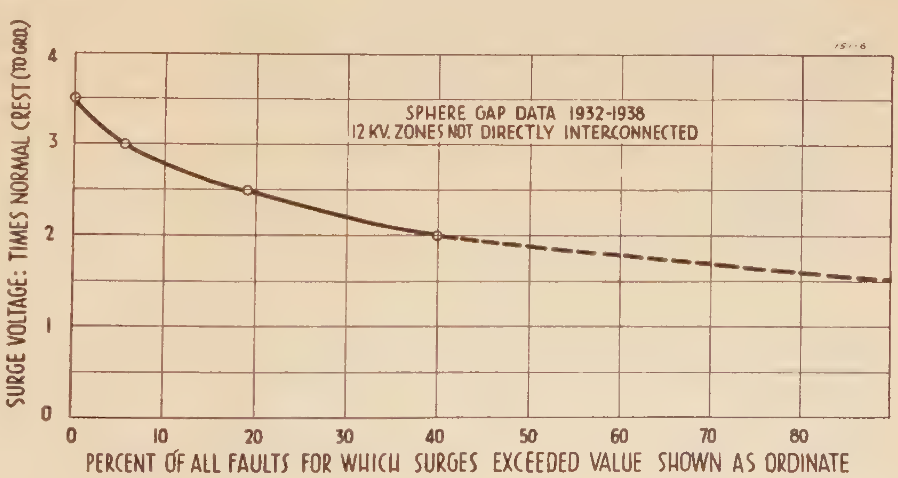


Figure 6 (below). Correlation of surges and failures



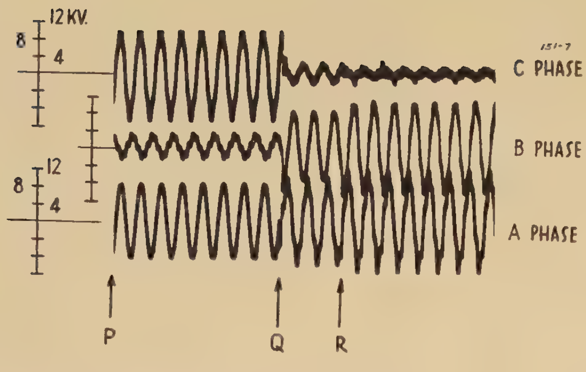


Figure 7. Simultaneous failure, type 2

P to *Q*: primary fault on *B* phase

Q: secondary fault initiated on *C* phase of another line; *B*-phase fault still on first line

Q to *R*: faults coexisting on *B* phase and *C* phase

R: *B*-phase fault cleared; *C*-phase fault still on but cleared later

system this surge, which constitutes the first portion or "make" transient of the system overvoltage, should not exceed $3.5E$. This value is obtained by adding a maximum expected cancellation transient of $2.5E$ to the normal steady-state value of E.

B. The Steady-State Fault Condition

After the transient of the applied cancellation wave has died out, the network conditions may be pictured as the sum of the normal steady state and the steady state of the cancellation generator. More simply, however, the conditions are obtained directly by the methods of symmetrical components. It is easily verified that for Chicago conditions with generator neutral grounding, which is three ohms resistive, or derived neutral grounding, which is three ohms inductive, the steady-state overvoltage on the unfaulted phases will not exceed $\sqrt{3}E$.

C. The "Break" Transient

The surge that results from the clearing of a fault is obtained precisely as in the fault initiation case except that a cancellation current, instead of a cancellation voltage, is "injected" at the fault. In this case, the transient effects the transition from a peak voltage of $\sqrt{3}E$ down to E whereas the reverse is true in the fault initiation case. It is reasonable to expect, therefore, greater total transient voltages on the fault "make" than on the break, assuming in all cases no restriking of the arc.

Some complete records of 12-kv surges were obtained in a series of 15 staged fault tests made at Northwest station in Chicago. The faults were thrown directly on the system, which was in normal everyday service. In each of the tests, a line-to-ground fault was applied by a special breaker to *A* phase of one outgoing line on the line side of the one-half-ohm line reactor. In some of the tests the 12-kv station bus was sectionalized to split the Northwest zone 12-kv system into two entirely independent parts (refer to figure 2). In the remainder of the tests the two busses were tied, which is the normal system setup. Four cycles prior to the application of the fault, the following oscillographs were initiated:

1. Cathode-ray oscillograph capacitatively coupled to *C* phase of the 12-kv station bus. Since the faults were applied on *A* phase, the transient overvoltages would appear on *C* and *B* phases. A film speed of six inches per cycle was used.

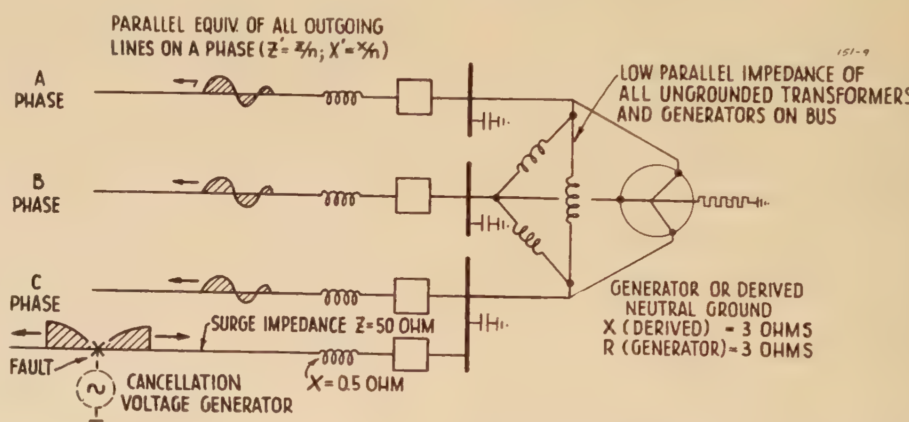


Figure 9. Cancellation wave on 12-kv system

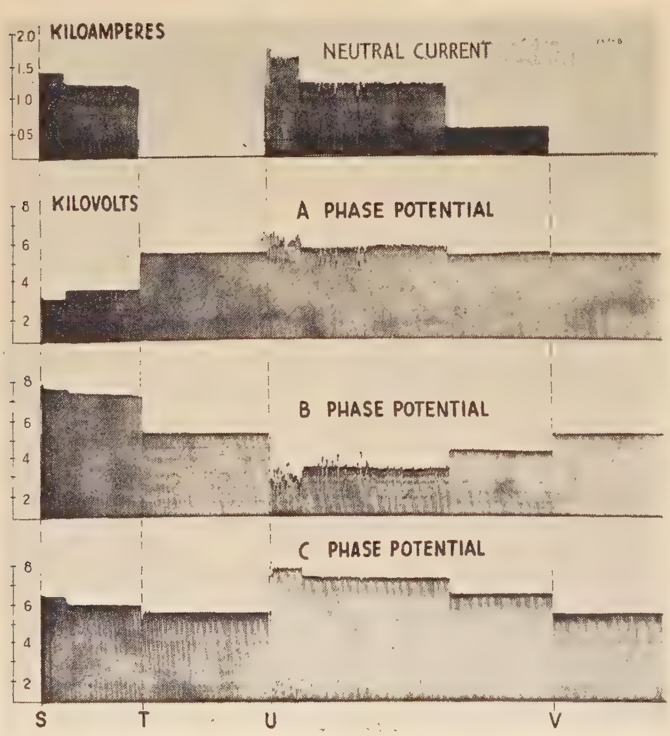


Figure 8. Simultaneous failure, type 4

S to *T*: primary fault on *A* phase

T: fault cleared, system normal from *T* to *U*

U to *V*: secondary fault on *B* phase

2. Magnetic oscillograph to record *A*, *B*, and *C* phase potentials on both sections of the 12-kv station bus.

3. Magnetic oscillograph to record the current in the system neutral and *A*-phase fault current

The *C*-phase potentials recorded by the cathode-ray oscillograph in two of the tests are shown in figure 10. The *A*-phase fault in these two cases consisted of a one-inch arc in air between copper bars. Eight cycles after the initiation of the faults they were cleared by the line breaker. Under each of the *C*-phase potential records, there is entered the cancellation potential, which starts at the time of fault and is equal and opposite to the normal potential on *A* phase. The transient resulting from the application of the cancellation wave is seen to last about one cycle. The first portion of the transient, corresponding to the first half cycle of the natural frequency of this transient, is seen to correlate, as it should,

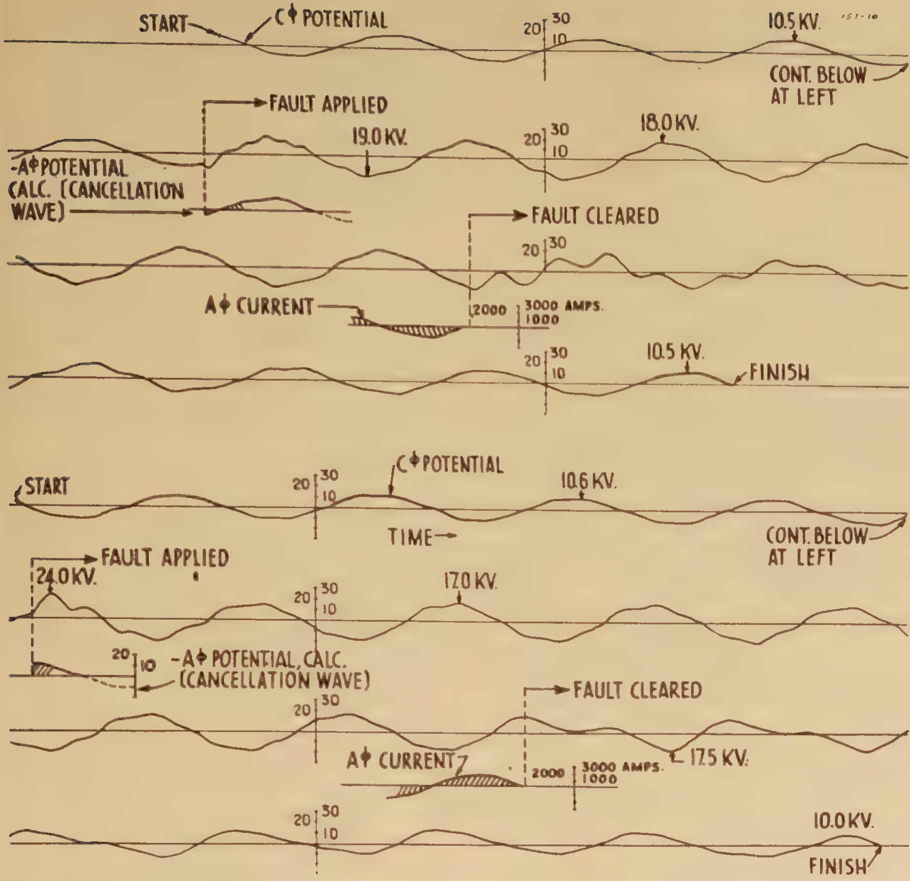


Figure 10. Oscillograms of staged fault tests

a (above)—12-kv zone sectionalized
b (below)—12-kv zone not sectionalized

exactly in both magnitude and polarity with the cancellation potential at the time of fault.

For the test in figure 10*a* the 12-kv bus was sectionalized, resulting in a higher transient frequency than in 10*b* where the systems were tied. The transient frequency did not exceed 500 cycles per second in any of the tests. The absence of higher frequencies, for the detection of which the cathode-ray oscillograph was well adapted, checks the conclusion derived from the spark-gap studies.

The overvoltage during the steady state of the fault is seen to be very close to $\sqrt{3}E$ as expected.

The transient overvoltage accompanying the clearing of the fault was less than $\sqrt{3}E$ in both cases shown in figure 10. Intermittent arcing is not indicated by any of the records obtained. The fault current during the break period is indicated under both oscillograms of figure 10. As is to be expected, the break occurred near a current zero.

The results of the remaining 13 fault tests are in accordance with the two cases described. In no case did the break transient give voltages in excess of $\sqrt{3}E$ and in no case was the faulted steady-state overvoltage in excess of $\sqrt{3}E$. In 5 of the 15 tests a surge voltage of between 24 and 26 kv ($2.27E$ to $2.45E$) was measured within one cycle of the initiation of the fault. In all of these cases the grounding was of the derived neutral type. In four tests with generator (resistance) grounding, the maximum surge potential did not exceed $2E$.

Summary

The highest transient overvoltages on the Chicago 12-kv system occur at the inception of single line-to-ground faults. They may be thought of as resulting from the superposition of a "cancellation wave" on the normal steady-state voltage of the system. The transient is not a high-frequency phenomenon and is not generated by an "intermittent-arcing" mechanism. The maximum crest values reached are in the neighborhood of $3.5E$ and persist for only the first cycle or two of the fault. For the remainder of the fault, including the clearance switching, the maximum overvoltage is $\sqrt{3}E$. These overvoltages may cause secondary (simultaneous) failures in any part of the connected system where the insulation is unable to withstand them for the short times they persist.

Report on Apparatus Bushings

AIEE JOINT COMMITTEE ON BUSHINGS

THE AIEE joint committee on bushings presented a report at the 1940 winter convention in which the committee proposed uniform requirements for the electrical characteristics of outdoor apparatus bushings. Since that time the committee has continued its work and has now completed a tabulation of proposed requirements for indoor and outdoor apparatus bushings rated 2,500 volts and higher.

The scope of the committee includes bushings for circuit breakers, transformers, regulators, and similar apparatus. It does not include wall and roof bushings potheads, and insulators for back-connected disconnecting switches.

The recommendations of the committee are based on the theory that an ample margin of insulation strength should be provided above the voltage to which the bushings may be subjected in service, including dynamic overvoltages, switching surges, and lightning surges up to the level of protection which can be provided with modern lightning protective devices. The impulse characteristics suggested are in accord with the values proposed by the joint AIEE-EEI-NEMA committee on co-ordination of insulation. All tests are to be made in accordance with a test code for apparatus bushings which is being prepared and which will be included in a proposed standard for apparatus bushings. The recommended values are expressed in terms of "withstand voltages" rather than "flashover voltages."

In order to avoid conflict with certain small indoor bushings which will not meet these requirements and to allow time for modifying the design of such bushings it is proposed to delay making these requirements mandatory for such small indoor bushings until January 1, 1943. It is understood that these requirements will be applied to any new design or redesigns made prior to that time.

The proposed requirements for the electrical characteristics of apparatus bushings are given in table I.

Paper 41-76, recommended by the AIEE committees on protective devices, electrical machinery, and power transmission and distribution, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 18, 1940; made available for preprinting December 18, 1940.

Personnel of AIEE joint committee on bushings: R. T. Henry, *chairman;* F. S. Brown, J. E. Clem, I. W. Gross, L. H. Hill, J. T. Lusignan, A. C. Monteith, J. R. North, E. Peipho, M. S. Oldacre, A. J. A. Peterson, R. E. Pierce, C. B. Springer, P. C. Turk, F. J. Vogel, and L. Wetherill.

Table I. Proposed Standard Withstand Test Voltages for Apparatus Bushings

Insulation Classification[a] (Kv)	Low-Frequency Test RMS Kv[b]: Outdoor Bushings: Large Apparatus[e] 1 Min Dry	Large Apparatus[e] 10 Sec Wet	Small Apparatus[f] 1 Min Dry	Small Apparatus[f] 10 Sec Wet	Indoor[g] Bushings 1 Min[c] Dry	Impulse Test 1.5x40-Microsecond Full Wave Crest Kv[b,d]: Outdoor Bushings: Large[e] Apparatus	Small[f] Apparatus	Indoor[g] Bushings
1.2			10	6			30	
2.5	21	20	15	13	20	60	45	45
5.0	27	24	21	20	24	75	60	60
8.7	35	30	27	24	30	95	75	75
15	50	45	35	30	45[h]	110	95	110[h]
23	70	60	70	60	60	150	150	150
34.5	95	80	95	80	80	200	200	200
46	120	100	120	100		250	250	
69	175	145				350		
92	225	190				450		
115	280	230				550		
138	335	275				650		
161	385	315				750		
196	465	385				900		
230	545	445				1,050		
287.5	680	555				1,300		
345	810	665				1,550		

NOTES: [a] Bushings of a given insulation classification are in general recommended for apparatus having a rating up to and including the insulation classification of the bushing and may be used for apparatus of a higher voltage rating when adequate for the particular application.

[b] All values are withstand test values without negative tolerance.

[c] Wet test values are not assigned to indoor bushings.

[d] Either positive or negative waves may be used—whichever gives the lower value.

[e] Bushings for use in large apparatus are those intended for use in transformers rated above 500 kva, outdoor circuit breakers, and other apparatus of corresponding importance.

[f] Bushings for use in small apparatus are those intended for use in transformers rated 500 kva and less and other apparatus of corresponding importance.

[g] Bushings for use in indoor apparatus are those intended for use in indoor-type circuit breakers, instrument transformers, and other indoor apparatus except dry-type instrument transformers, air-cooled transformers, air-cooled regulators, and bushings used primarily for mechanical protection of insulated cable leads.

[h] Bushings for small indoor apparatus may be supplied to withstand a low-frequency test of 38 kv and an impulse test of 95 kv.

The Detection of Initial Failure in High-Voltage Insulation

J. B. WHITEHEAD
FELLOW AIEE

M. R. SHAW, JR.
ASSOCIATE AIEE

Introduction

IN a series of accelerated life tests[1] on laboratory samples of impregnated-paper insulation of the type commonly used in high-voltage cables, certain methods have been employed for limiting the breakdown current and thereby the attendant burning of the insulation. In this way it has been found possible to obtain partial failures in which the breakdown is limited to only a portion of the insulation wall, say one-half or one-third of the total number of layers, the remaining layers being apparently unaffected. In these partial failures, the burning is very slight and it is possible to obtain a very good idea as to the location of the initial point of failure and the nature of its subsequent progress. With one of the methods used it has been possible on occasion to limit the breakdown to only two layers of paper and to study the extension of the failure through adjacent layers. The method gives great promise for the study of the mechanism of breakdown under laboratory conditions. In this paper we are reporting some of the preliminary results of a more extended program of study still under way.

Probably the condition most conducive to the beginnings of failure under normal conditions of service is the presence of gas bubbles, pockets, or layers within the body of the insulation. Potential gradients at which ionization can begin in such gas pockets or layers are often exceeded in equipment for only moderately high voltages. Gas layers in the insulation circuit may be caused by imperfect impregnation, or as the result of bending or other mechanical strains in the normal processes of manufacture, transportation, and installation. In other cases gas spaces may result from the temperature variations attendant upon load changes. The accelerated life tests already referred to have indicated still a further cause of gas liberation, namely high-voltage stress on the oil layers or other free oil in impregnated-paper insulation, such as the channels between successive turns of paper tape. Study of the partial failures referred to clearly indicates that initial failure usually starts in the oil channel and is accompanied by the evolution of gas.

Under alternating stress gaseous ionization and other initial discharges occur first on the crests of the alternate half waves. This gives the discharges an impulse character so that in conjunction with the capacitance and inductance of the high-voltage circuit the discharges take on an oscillatory character. This fact has afforded a simple means of detecting the presence of such discharges and has been utilized almost exclusively by those who have studied the phenomenon.

Ripples on the crests of a-c voltage waves due to gas discharges were apparently first shown by Edward Bennett,[2] using the electromagnetic oscillograph. With the development of the cathode-ray oscilloscope, visual observation of the ripples is a simple matter, and this instrument is commonly used as a qualitative detector in all studies of this character. The earlier studies of Paine[3] and coworkers are well known. The possibility of more sensitive and quantitative studies has been shown by Arman and Starr,[4] the distinguishing characteristic of whose work is a bridge, filter, and amplifier circuit free from disturbance due to local discharges in the high-voltage circuit and extraneous to the specimen under study.

Measuring Equipment

In the present work the method of Arman and Starr, with certain modifications and extensions, has been used for the detection of initial internal gaseous discharge and the quantitative study of the subsequent stages of the discharge, first on impregnated-paper insulation originally containing no free gas, and also on several types of insulating wall with gas pockets and oil channels of controlled dimensions.

Bridges

Two types of bridge have been used. The first for voltages up to 30 kv was the modified Schering bridge due to Whitehead.[5] This bridge was in constant use for the measurement of power factor in the series of accelerated life studies on impregnated-paper insulation of cable type already referred to. At regular intervals in the life runs of these specimens the detection circuit of the present research was connected to the Schering bridge, following the periodic measurement of 60-cycle power factor in the life runs. In this way it was possible to fix within a few hours the time at which internal ionization began and in some measure to correlate the progress of internal ionization with changes in 60-cycle power factor and applied voltage.

For closer study of internal discharges, it appeared desirable to work with thinner specimens in which the critical gradients would be reached with the specimen continuously in the bridge circuit. Accordingly the simplified form of Schering bridge shown in figure 1 was constructed. C_x is the specimen and C_a is the air capacitor. Auxiliary studies indicated that up to ten kilovolts, the limit of bridge operation, the high-voltage circuit including the air capacitor was free from internal discharges.

Bridge Transformer

The detection equipment was connected to either of the bridges through a high-quality bridge transformer, with electrostatic shielding between the pri-

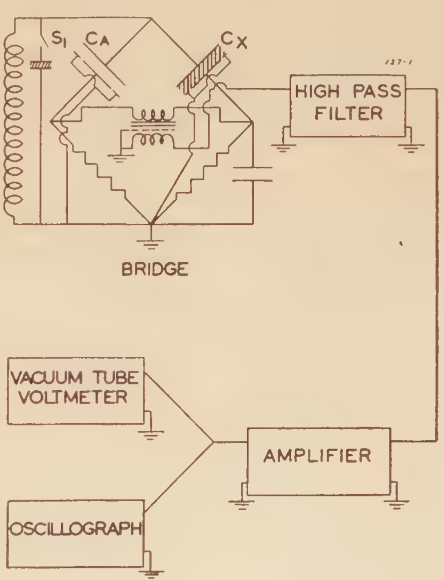


Figure 1. Discharge bridge circuit and connection of apparatus

Paper 41-27, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted July 30, 1940; made available for preprinting December 4, 1940.

J. B. Whitehead is professor of electrical engineering and director of the school of engineering at The Johns Hopkins University, Baltimore, Md. M. R. Shaw, Jr., affiliated with The Johns Hopkins University at the time this paper was written, is now with the Corning Glass Works, Corning, N. Y.

1. For all numbered references, see list at end of paper.

mary and secondary windings, both of which were capacitively balanced with respect to ground. This permitted one end of the output winding of the transformer to be grounded without disturbing the symmetry of the bridge circuit. This is important because it permits the grounding of one side of the whole amplifying and detecting circuit, thereby permitting that the whole circuit be enclosed in a grounded shield. Circuit changes on the output side of the transformer thus have no influence on the balance of the bridge. The voltage ratio of the transformer was measured between 1 and 50 kilocycles and found to be closely uniform up to about seven kilocycles, and to decrease somewhat beyond. The over-all impedance ratio of the transformer based on its turn ratio was 4.4 to 1 which brought about an impedance match between the bridge and the high-pass filter.

Filter

A filter having three full sections was adopted. The cutoff frequency, 3,600 cycles, was chosen because it was low enough to pass the band of oscillations due to internal discharges and high enough to reject any high harmonics of the 60-cycle charging current. The terminal impedance at each end was 5,500 ohms. Impedance matching at the input end of the filter was accomplished by the bridge output transformer. Impedance matching with the amplifier was effected by placing a noninductive resistor of 5,500 ohms across the filter.

Amplifier

A resistance-capacitance coupled amplifier was inserted between the filter and the detector (see figure 1). Details of the amplifier are shown in figure 2 with circuit constants given. At 10,000 cycles, the frequency at which all calibrations were made, the amplification factor was

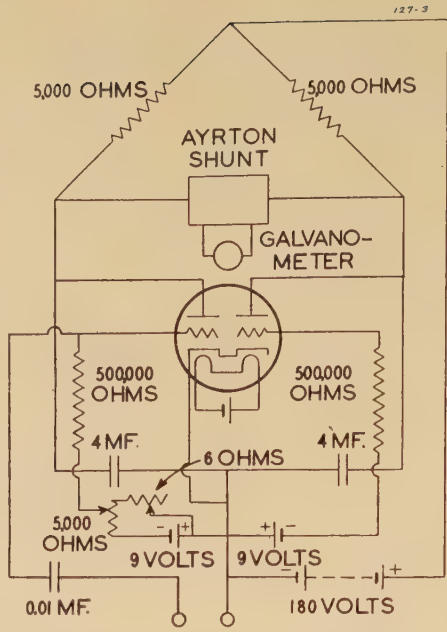


Figure 3. Circuit diagram of balanced vacuum tube voltmeter using type 6N7 tube

4,700. As a function of the input voltage saturation took place at an input voltage of 5.5 millivolts. Consequently all readings recorded were obtained with input voltage to the amplifier of five millivolts or less.

Detectors

A standard model of a well-known make of cathode-ray oscilloscope was used for qualitative measurements. An amplifier of gain 40 was incorporated in the oscilloscope. This, in conjunction with the external amplifier made it possible to realize an over-all gain of 40×4,700, or 188,000 at 10,000 cycles. This instrument is extremely useful, permitting ready and rapid visual observation of conditions obtaining in the circuit.

For quantitative measurements a balanced vacuum tube voltmeter as indicated in figure 3 was used. This arrangement is independent of small changes of battery voltage and the combination of duplex tube, decade resistance boxes, and Ayrton shunt for the galvanometer, results in a very sensitive quantitative instrument. The calibration of the meter with galvanometer of 120 megohms sensitivity with various settings of the shunt was found to hold over the range 60 cycles to 50 kilocycles. The voltage required for one centimeter deflection at maximum sensitivity was 13,000 microvolts. The over-all amplification factor between the input of the bridge transformer and the output of the amplifier as function of frequency may be had from the data in table I. At ten kilocycles the over-all amplification factor was 1,830. Hence a voltage of 13,000/1,830 or 7.1 microvolts gave a galvanometer deflection of one centimeter. In figure 4 the voltage for one centimeter deflection is plotted over the range 1 to 50 kilocycles.

Tests and Calibration of Equipment

Ten-Kilovolt Discharge Detection Bridge

A first necessary step in the use of this method is to balance the bridge for minimum effect in the detection apparatus, of local high-frequency discharges external to the specimen itself. Accordingly a small discharge gap consisting of a few layers of varnished cambric between two brass electrodes was connected between the bridge and the high side of the supply transformer, as shown in figure 1. The primary voltage is increased until discharge occurs in the gap, the latter being adjusted for discharge at relatively low voltage. The detecting circuit is then connected using the oscilloscope as indicator. The bridge is then balanced so as to bring to a minimum the signal on the screen of the oscilloscope. This minimum could be made practically zero, even though the ionization in the gap was strong enough to be audible several feet away.

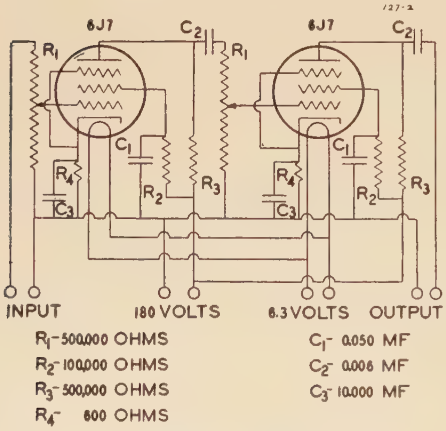


Figure 2. Amplifier

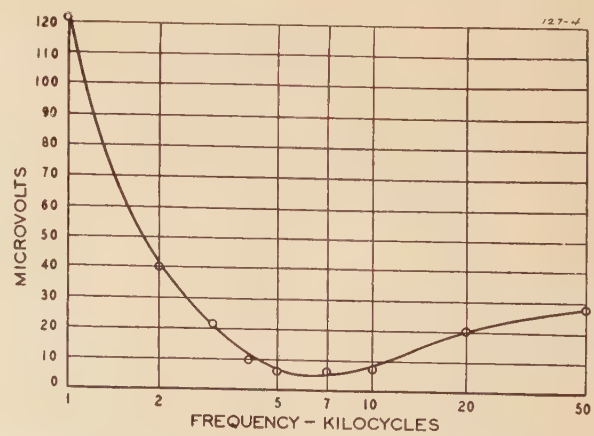


Figure 4. Voltage necessary at bridge terminals to cause one centimeter galvanometer deflection

In this method it is to be noted that stress is applied to the specimen under test at 60 cycles but that only a fraction of the total discharge current over a comparatively narrow band of frequencies reaches the detecting circuit. This fraction passes through the several elements of the complete circuit before reaching the final detecting instrument. It seemed advisable, therefore, to test the over-all sensitivity and accuracy of the equipment by comparison with the known properties of the breakdown strength of air in thin layers as related to pressure, through Paschen's law. The apparatus was a guarded capacitor consisting of a layer of air backed by a layer of glass for preventing complete breakdown. For the range of pressure between 15 centimeters and 76 centimeters Hg, the voltage stresses for initial ionization, as determined by the equipment, and as computed from Paschen's law are shown in figure 5 for the temperatures indicated. In figure 6, the critical stress as a function of the electrode spacing is shown in the solid curve; for comparison, the experimental results of Dubsky[6] on thin air films, are also plotted.

30-Kv Schering Bridge

The large physical size of this bridge resulted in enough pickup of extraneous high-frequency disturbance to serve as a guide in the preliminary balance without recourse to a discharge gap. The effect of the external discharges was readily balanced out by adjustment of the resistance arms and the variable capacitor.

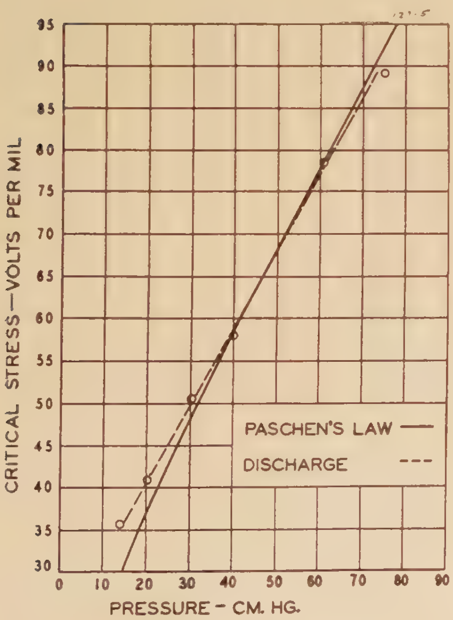


Figure 5. Critical stress for gaseous discharge between parallel plates as detected by discharge bridge and as function of pressure

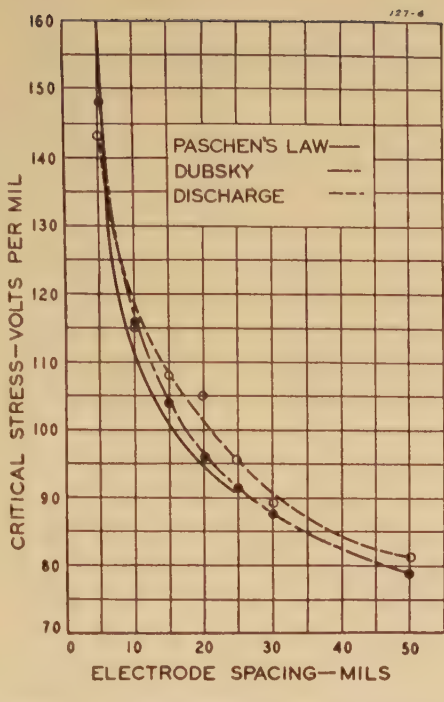


Figure 6. Critical stress for gaseous discharge between parallel plates as detected by discharge bridge and as function of separation of plates

In this condition the bridge could be used for the study of initial discharges in specimens of impregnated-paper cable insulation on life test and at higher voltage gradients in these life specimens than possible with the ten-kilovolt bridge.

Experimental Results

The method was applied to several types of insulation as follows: (*A*) laboratory specimens of impregnated paper as found in high-voltage cables, and originally free from gas bubbles or pockets; (*B*) single oil channels as found in cable insulation; (*C*) channels and bubbles of air of known dimensions, and subject to visual observation. The general method of test was the determination of the voltage gradient at which internal gaseous discharge begins and the increase in the "volume" of the latter with increasing gradient. At an early point it was found that the elapsed time of application of stress may have an important influence on both the critical discharge stress and on the "volume" of discharge at sustained high stress. The readings of the detecting instrument are obviously proportional to an integrated value of a product of the number of discharge areas and the intensity of discharge current in each area. In what follows the word "volume" has been used to indicate this integrated product.

(A). Cable Insulation

In the accelerated life tests on standard types of impregnated-paper insulation, the test samples consisted of 16 layers of 0.005-inch wood pulp paper one inch wide, spiraled cable fashion on one-inch diameter smooth brass tubes with $33^1/_3$ per cent overlay and a butt spacing of approximately $^1/_{64}$ inch. These samples were dried and impregnated with a low-viscosity high-grade cable oil in the usual way, and tested to break down under the impregnating oil. The accelerated step-up life test started at an average stress of 400 volts per mil on the specimen and the applied stress was increased by 3.12 per cent every four hours, thus giving a geometric increase such as to bring the stress to 700 volts per mil within three days. Under this program, the life of the specimen was from 60 to 80 hours, and the breakdown gradients from 600 to 800 volts per mil, at 50 to 65 kv on the test transformer.[1]

At four-hour intervals the life test was interrupted for the measurement of power factor over the range 100 to 400 volts per mil. Following the power-factor measurement, the galvanometer was cut out of

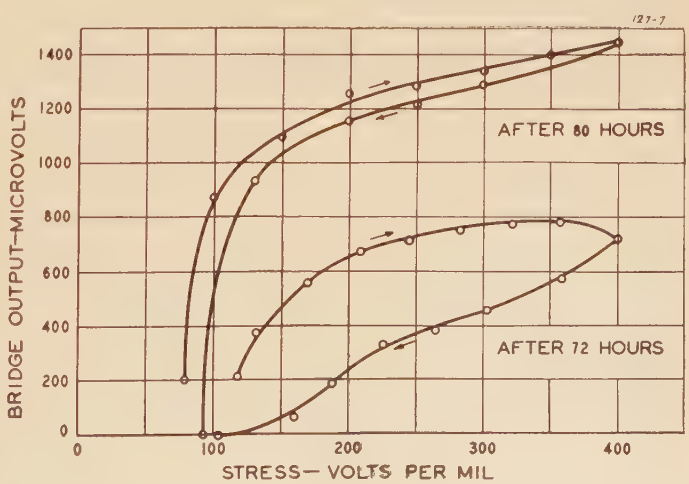


Figure 7. Ionization in impregnated-paper insulation

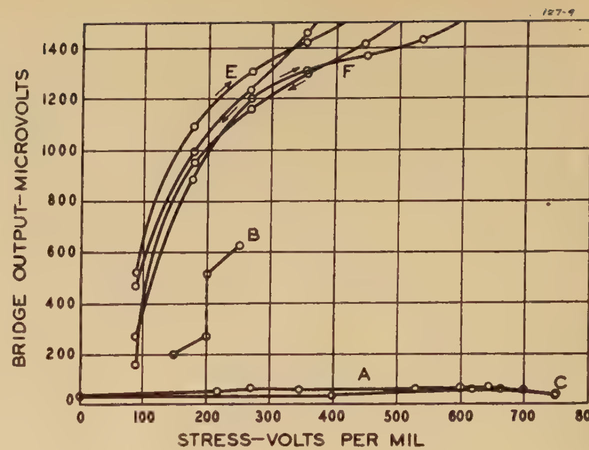
the Schering bridge and the discharge equipment connected. The bridge was then balanced for a negligible minimum reading of the discharge equipment due to external discharges in the high-voltage wiring, up to a voltage somewhat below that at which internal discharges begin in the sample. The equipment was then ready for observation.

First observation was made on the specimen after it had been on test for 24 hours reaching a stress of 467 volts per mil. No internal discharge was found at this point nor at subsequent intervals of 12 hours up to 60 hours with a final stress of 618 volts per mil. Positive readings of internal discharge were first observed after the specimen had been on test for 72 hours with a final stress of 679 volts per mil. In these observations it is to be recalled that the specimen was removed from the life test voltage, power factor and internal discharge being measured over the range 100 to 400 volts per mil.

The relation between internal discharge and stress, finally found after 72 hours of test, is shown in the lower curve of figure 7. As will be seen the volume of discharge increases with the stress, tending, however, to a maximum value and then to a somewhat lower value at the maximum stress of 400 volts per mil. The volume of discharge on decreasing stress is seen to be markedly lower than for increasing stress. In another test, the stress was held constant at 400 volts per mil and it was found that the volume of discharge decreased with time and ultimately ceased entirely. This indicates that when internal discharge occurs, it will continue at substantially lower values of applied stress. However, there is a lower value of stress at which there will be a decrease and final disappearance of the volume of internal discharge. This decrease is probably due to gas absorption and oil sealing, or perhaps to internal burning or carbonization, short-circuiting the gas spaces involved.

Power-factor measurements at 60 cycles corresponding to the above sequence of

Figure 9. Ionization in impregnated-paper half-wall specimen



tests are given on the curve of figure 8. Point 7 is the value at the end of 72 hours before the discharge measurements were made. After sustained application at 400 volts per mil with cessation of internal discharge, the specimen was put back on high-voltage life test for one hour, then removed, and tested again for power factor and internal discharge. The power-factor value is given at point 8 and there was no evidence of internal discharge. The specimen was then returned to life test for eight hours with a final stress of 722 volts per mil, and during this interval two power-factor readings indicated the increase shown beyond point 8 in figure 8. The internal discharge now followed the upper curve of figure 7, which has the same general shape but greater magnitude than the earlier curve. The influence of time is still present though not so marked. It appears probable that owing to the higher stress, deterioration and new internal discharges are increasing more rapidly than the decreases shown in the tests at lower stress. On return to life test after these measurements, the specimen failed within two hours.

In order to be independent of the above life tests and to reach higher stresses at lower over-all voltage, similar specimens with only half the thickness of wall, were constructed, impregnated, and tested with the 30-kv Schering bridge. In this arrangement the stress could be carried to 800 volts per mil and internal discharge measurements made at all stresses up to this figure without interruption.

The specimen was first carried slowly up to 700 volts per mil with the result shown in curve *A* of figure 9. The level of discharge due to external influence is seen to be very low and uniform in the whole range of stress. After 12 hours rest, the power-factor stress relation shown by curve *A* of figure 10 was taken. The increase in power factor thus found seems to indicate that internal discharges are taking place in the specimen. None such were found however until after ten minutes' application of the maximum stress of 700 volts per mil, at which point a violent indication of internal discharge was found. The voltage was immediately removed and the specimen given a ten-minute rest. It was then found that internal discharge started at 100 volts per mil, with a further increase as indicated by curve *B* of figure 9. A power-factor observation taken at this point indicated an increase of value, and during the period of this measurement the volume of internal discharge increased as shown by the dotted portion of curve *B*, figure 9. Further increase of stress beyond 200 volts per mil gave a still further increase in the volume of discharge.

At the end of the foregoing test, the specimen was given a 70-hour rest period at the end of which period the relation between internal discharge and applied stress is shown in curve *C* of figure 9. The specimen is apparently in the same condition as when it was first subjected to test, perhaps slightly better. One hour at 700 volts per mil gave no indication of internal discharge. Increase to 750 volts per mil, maintained for 55 minutes, brought about the renewal of internal discharge. The voltage was immediately reduced to zero and then gradually reapplied, discharge beginning at 620 volts

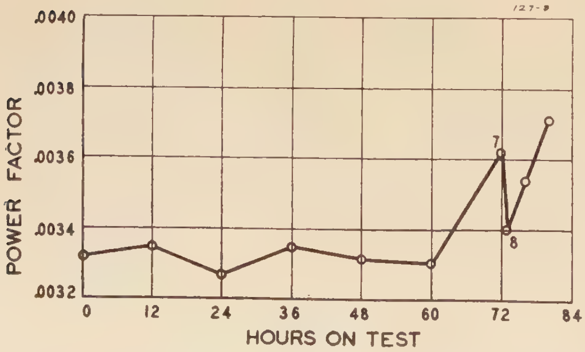


Figure 8. Power-factor variation before and after initial internal discharge

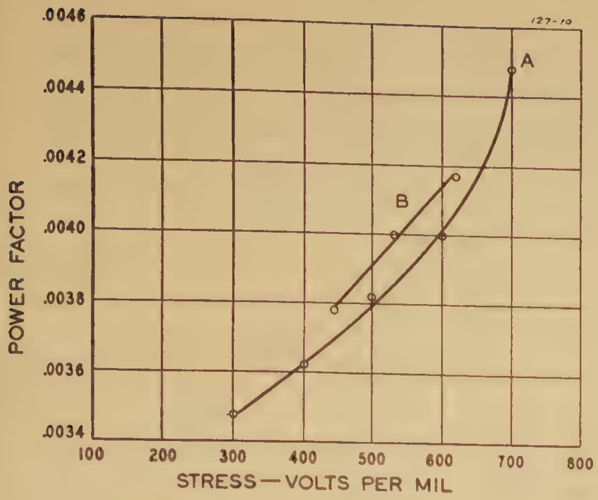


Figure 10. Power factor of half-wall specimen

per mil. The power factor had also increased (see curve *B* of figure 10).

Two discharge stress runs were then made, with a short-time interval between runs. The results are shown in curves *E* and *F* of figure 9. Note that the volume of discharge in the second run was less than in the first, suggesting a slight recovery in the interval between runs.

After another 12-hour rest period, the specimen was again found to be free of internal discharge after 700 volts per mil, maintained for eight hours. The stress was then increased to 750 volts per mil when internal discharge began immediately, but the specimen failed before a quantitative measurement could be taken.

(B). Oil Channels in Small Specimens

In order to investigate the value of stress at which internal discharges begin in an oil channel in impregnated paper, a group of two- and three-layer impregnated-paper specimens were prepared and tested between horizontal, parallel, polished brass plates. The three-layer specimens consisted of two sheets of impregnated paper and a third sheet in which a slit was made. In the two-layer specimens, one layer was continuous and the other contained a slit. The slits were the same width (0.0156 inch) as the oil channels in the life test specimen referred to above; their length was three inches. Drying and impregnation were in accordance with three-layer and two-layer specimens referred to above.

Preliminary tests were made with three-layer and two-layer specimens of continuous sheets of paper, and it was found that these could be carried to 1,100 and to 1,200 volts per mil respectively, and maintained for six hours without evidence of internal discharge.

For testing the specimens containing slit papers forming oil channels, the following schedule was used: (*a*) 15 minutes at 1,000 volts per mil in the oil channel (ratio of dielectric constants, impregnated paper to oil: 2); (*b*) three per cent per minute increase in stress to 1,600 volts per mil in channel; (*c*) five per cent increase in stress at five-minute intervals from 1,600 volts per mil to incipient failure.

This accelerated schedule is necessary to eliminate the influence of time found in the earlier studies. In two two-layer specimens, initial internal discharge was found at 1,530 and at 1,860 volts per mil in the oil channel; in the three-layer specimens the values found were 1,600 and 1,630 volts per mil. These values are somewhat higher than those reported by Whitehead[1] which were in the range 1,350 to 1,550 volts per mil. In the latter case, however, the specimens were under high stress a much longer time. In the present case all of the incipient discharges eventually produced punctures originating in the oil channel.

(C). Tests on Air Bubbles in Oil Channels

A special test cell permitted the insertion of air bubbles in the oil channel in a slit in impregnated paper. Visual observation was possible through the upper electrode, consisting of a salt solution in a tray with plate glass bottom. Special provisions permitted the operation of the cell up to ten kilovolts without disturbance in the detecting circuit due to discharges from the guard circuit.

With paper in place, the whole apparatus was evacuated to one millimeter Hg at 40 degrees centigrade for two hours, at which point all gas has ceased to come out of the oil. A test was then made at low stress which showed the absence of discharges. The upper electrode was then carefully moved to one side, exposing the channel. An air bubble was then introduced by means of an eye dropper, and the electrode then brought back into place.

The gaseous discharge as a function of applied stress was measured on bubbles of lengths, 47.2, 98.5, and 132 mils, and width of 15.6 mils. The quantitative results for bubbles of the same length varied somewhat but certain characteristics were invariably repeated. Three curves, for temperature 40 degrees centigrade are shown in figure 11. For shorter bubbles, the discharge in general increases with increasing stress and decreases with decreasing stress. For the longer bubbles the conditions become erratic and no definite behavior is indicated which may be correlated with the results on the cable specimens. Using the results on the shorter bubbles as a measure, it is suggested that the initial discharges in the cable specimens begin bubbles less than 0.1 inch in length, and 0.03 inch in width.

Discussion

The peculiar relationships between internal discharge, stress, and time noted in connection with the cable specimens may perhaps be best explained in terms of the frequent observation that first evidences of breakdown occur in the oil

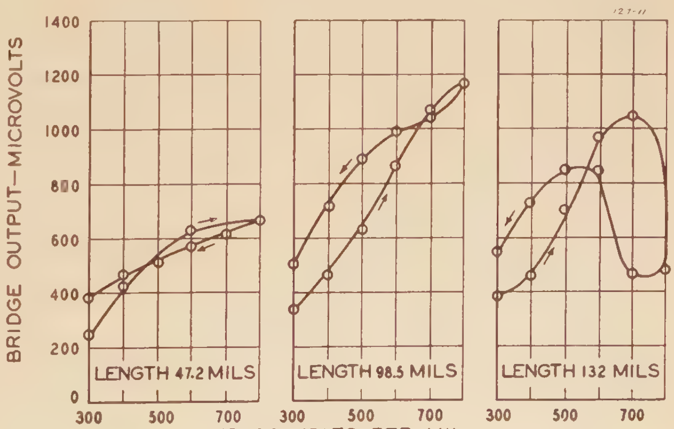


Figure 11. Ionization in air bubbles

channels and that the initial stages of this breakdown are accompanied by the liberation of gas. At initial discharge in the oil, corona formation results in the evolution of gas and polymerization. Once a bubble of gas is formed, it may be ionized at a value of stress much lower than that causing the original discharge. The gas bubble, however, is not stable and may be reabsorbed into the oil. This is responsible for the variation with time of the intensity or volume of discharge, and also for the complete recovery following a long rest period. The healing effect of time without stress is particularly noticeable in the thicker cable specimens on life test at higher stresses. Interruption of the high stress and subsequent measurement of power factor at very much lower stress provides opportunity for healing action due to gas absorption. It also probably accounts for the steady decrease of internal discharge even when stress is applied to the specimen, when this stress is substantially lower than that at which the internal discharge was first initiated.

The peculiar loops showing decreases of volume of discharge with increasing stress and vice versa noticed in the impregnated paper and air bubble tests may perhaps be explained as due to variations in pressure in gas pockets. A more or less rapid increase in pressure causing a reduction in the volume of discharge is followed by a slow release of pressure with corresponding increase in the volume of discharge.

The increase in the strength of the insulation with successive discharge cycles may possibly be explained by the process of polymerization. The wax which replaces the oil has high dielectric strength and prevents this particular spot from ionizing again. With increasing stress, discharge will first occur at a different point. It also appears possible that surface discharges, tree patterns, and the like, may at times result in the short circuit of a gas pocket, thus reducing the ionizing stress and causing a reduction and possible disappearance of the internal discharge, which may then only reappear in another cycle in another place, and at a higher stress.

Of particular interest is the evidence that the time of application of stress is an important factor in fixing the value of stress at which discharge appears; for example in the thin-wall cable specimens, the stress was taken up to 700 volts per mil without immediate evidence of discharge. Moreover at this high value of stress a considerable time was required before internal discharge appeared.

The tests on oil channels indicate that for short times the strength of these channels is quite high and probably very close to that of the oil alone. The lower values reported by Whitehead show the influence of time due perhaps, as suggested by him, to contact with the paper. The peculiar results found in the observation on air bubbles may perhaps be due to temperature, to saturation conditions in the gas, or to subsequent changes in volume or pressure in the gas. Further study is in progress, notably as to the time element, both under stress, and after its removal.

Table I

Frequency (Kilocycles)	Loss or Gain* (Decibels) Amplifier	Transformer	Filter	Total	Amplification Factor
1	+74.0	− 3.4	−30.0	+40.6	107
2	+74.0	− 3.4	−20.0	+50.6	338
3	+74.0	− 3.4	−15.0	+55.6	600
4	+73.8	− 3.4	− 8.0	+62.4	1,300
5	+73.8	− 3.4	− 4.2	+66.2	2,040
7	+73.5	− 4.2	− 2.3	+67.0	2,240
10	+73.3	− 8.0	0	+65.3	1,830
15	+72.2	−11.3	− 1.4	+59.5	920
20	+70.8	−12.0	− 3.0	+55.8	620
30	+69.3	− 9.6	− 4.0	+55.7	606
40	+67.2	− 7.6	− 4.6	+55.0	561
50	+66.0	− 7.6	− 5.0	+53.4	470

*+ indicates a gain; − indicates a loss.

Conclusions

(1). Internal discharges occur in impregnated-paper insulation well in advance of failure and once initiated continue at stresses much below the breakdown values commonly attributed to this type of insulation.

The stresses at which initial discharges begin in insulation originally free of gas bubbles are from seven to eight times as high as the stresses usually obtaining in power cables.

(2). An improved method for detecting initial internal discharges in insulating materials is described. Calibrated in terms of gaseous ionization in thin air films of different thicknesses and at different pressures, it is found to detect initial discharge and its variation in accordance with Paschen's law.

(3). The seat of incipient failure in the samples of impregnated-paper insulation here studied is the oil channel between successive turns of paper tape. An initial discharge is followed by the evolution of gas which is ionized on successive alternating wave crests; the resulting oscillations are utilized for detecting the initial discharge and as a measure of the subsequent volume of discharge.

(4). Specimens stressed to the point where initial discharge begins may be brought back to apparently normal condition by allowing them to stand without stress for a period of time. This is attributed to the absorption of gas by the oil.

(5). A plus or minus variation with time under stress below the critical value, may occur in the volume of internal discharge. This is attributed to changes in pressure, or in volume of ionized gas, or to the absorption of gas by the oil.

Bibliography

1. The Dielectric Strength and Life of Impregnated-Paper Insulation, Part I, **J. B. Whitehead.** AIEE Transactions, volume 59, 1940, pages 715–20.

2. An Oscillograph Study of Corona, **Edward Bennett.** AIEE Transactions, volume 32, 1913, page 1787.

3. Bulletin No. 260, **J. T. Tykociner, H. A. Brown,** and **E. B. Paine.** Engineering Experiment Station, University of Illinois, 1933, page 6.

4. The Measurement of Discharges in Dielectrics, **A. N. Arman** and **A. T. Starr.** *Journal* IEE, volume 79, July 1936, page 67.

5. Influence of Residual Air and Moisture in Impregnated-Paper Insulation, **J. B. Whitehead** and **F. Hamburger.** AIEE Transactions, volume 47, 1928, page 314.

6. The Dielectric Strength of Air Films Entrapped in Solid Insulation and a Practical Application of the Problem for Alternator Coils and Cables, **F. Dubsky.** AIEE Transactions, volume 38, 1919, pages 537–58.

A Construction Theorem for Evaluating Operational Expressions Having a Finite Number of Different Roots

PAUL C. CROMWELL
ASSOCIATE AIEE

IN the course of the past 25 years Heaviside's direct operational method of solving differential equations has, to a large extent, been replaced by solutions involving functional transformations. While mathematically sound this trend has resulted in placing a powerful analytical tool far above the mathematical equipment of the average engineer. With the exception of the celebrated expansion theorem or the method of partial fractions no *direct* method appears to have been discovered by which the average engineer or engineering student could solve even relatively simple differential equations by Heaviside's calculus. Several expansion theorems have been developed[1,2,3,4] to cover cases where repeated roots are present but none of these have been set up in a form which could be used by undergraduates. It does not appear that any direct general procedure has ever been suggested to cover the usual type of asymptotic solutions which appear in problems in electrical engineering.

It is the purpose of this paper to develop a direct method for evaluating operational expressions involving a finite number of different roots. For rational expressions the theory is based upon the usual procedure in obtaining the particular integrals of ordinary differential equations with constant coefficients. The procedure is heuristically extended to irrational operators by analogy so that its greatest utility lies in the field of asymptotic solutions.

The term "construction" has been applied to this theorem because the operations to be performed are only indicated as contrasted with the general solutions which characterize the "expansion type" theorems.

In order that this paper may be of value to engineers who are not familiar with integration in the complex plane no mathematically rigorous proof will be given. An outline for such a proof is presented in the last section.

Definitions and Fundamental Operations

Consider the steps necessary in solving for the particular integral of an ordinary linear differential equation with constant coefficients. As an example take the equation

$$(D+a)i=\epsilon^{bt}t \tag{1}$$

where D is defined as the usual derivative operator of differential equations d/dt and t is the independent variable time. i is the dependent variable and is usually the current in amperes for electrical work. a and b are constants and $b>-a$. To solve for the steady-state current, or particular integral, divide both sides of the equation by $(D+a)$

$$i_s=\frac{1}{(D+a)}\epsilon^{bt}t \tag{2}$$

The exponential can now be "shifted" from right to left.

$$i_s=\epsilon^{bt}\frac{1}{(D+a+b)}t \tag{3}$$

The next step is to expand the denominator in ascending powers of D by division or by the binomial theorem

$$i_s=\frac{\epsilon^{bt}}{a+b}\left(1-\frac{D}{(a+b)}+\frac{D^2}{(a+b)^2}\cdots\right)t \tag{4}$$

Performing the operations indicated

$$i_s=\frac{\epsilon^{bt}}{a+b}\left(t-\frac{1}{a+b}\right) \tag{5}$$

which is the steady-state solution for equation 1 Notice that no arbitrary constants appear and that the process involves differentiation but no integration. This is important since the usual Heaviside operator p can be substituted in place of D. $1/p$ is to mean $\int_0^t dt$. In order to identify this general process a new operator will be defined.

Definition of a Bar Operator: Two bars placed over an operator $\overline{\overline{(p+a)^n}}$ are to indicate the complete operation of expanding the operator in ascending powers of p by the binomial theorem and performing the indicated differentiations. n may be a positive or negative real number including fractions. If this operator operates on a linear combination of powers of t multiplied by an exponential the first operation is always a "shift" of the exponential.

By the use of the bar operator the result shown in equation 5 can be expressed as

$$i_s=\overline{\overline{(p+a)^{-1}}}\epsilon^{bt}t \tag{6}$$

Notice that equation 6 without the double bar might be confused with the equivalent complete operational solution which would include a transient term not indicated by (6).

These bar operators have several properties which are of interest when used with the fundamental and well-known operational expression

$$\frac{p}{(p+a)^n}1=\frac{\epsilon^{-at}t^{n-1}}{\Gamma(n)} \tag{7}$$

n may be a positive integer, proper or improper fraction and a is a constant, real or complex. These properties are easily proved so that no proof will be given here.

1. Bar operators are commutative. That is, they may be used in any order to bring about the same result.

$$\overline{\overline{(p+b)^m}}\,\overline{\overline{(p+c)^r}}\left[\frac{\epsilon^{-at}}{\Gamma(n)}t^{n-1}\right]=\overline{\overline{(p+c)^r}}\,\overline{\overline{(p+b)^m}}\left[\frac{\epsilon^{-at}}{\Gamma(n)}t^{n-1}\right] \tag{8}$$

Where $a\neq b\neq c$ and r and m are positive.

2. Reciprocal bar operators perform reciprocal operations.

$$\overline{\overline{(p+b)^n}}\left[\overline{\overline{(p+b)^{-n}}}\frac{\epsilon^{-at}}{\Gamma(n)}t^{n-1}\right]=\frac{\epsilon^{-at}}{\Gamma(n)}t^{n-1} \tag{9}$$

3. In the case of "equal roots"

$$\overline{\overline{(p+a)^m}}\left[\frac{\epsilon^{-at}}{\Gamma(n)}t^{n-1}\right]=\frac{\epsilon^{-at}t^{n-m-1}}{\Gamma(n-m)} \tag{10}$$

m and n are both positive integers or fractions. If $(n-m)$ is a negative integer or zero the gamma function of this number is infinite and the result is zero.

4. The case of unequal roots

$$\overline{\overline{(p+b)^m}}\left[\frac{\epsilon^{-at}}{\Gamma(n)}t^{n-1}\right]=\epsilon^{-at}(b-a)^m\overline{\overline{\left(1+\frac{p}{b-a}\right)^m}}\frac{t^{n-1}}{\Gamma(n)} \tag{11}$$

Paper 41-37, recommended by the AIEE committee on basic sciences, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted June 16, 1939; made available for preprinting December 10, 1940.

PAUL C. CROMWELL is assistant professor of electrical engineering, college of engineering, New York University, New York, N. Y.

The author wishes to express his appreciation to Professor Kurt O. Friedrichs of the mathematics department, New York University, to whom he is deeply indebted for many valuable criticisms and suggestions during the preparation of this paper. Also to Professor Ernst Weber, electrical engineering department, Polytechnic Institute of Brooklyn, for his helpful suggestions and interest in the project.

1. For all numbered references, see list at end of paper.

n is positive but m may be positive, negative, or a fraction. $a \neq b$.

5. If $b=0$ and $n=1$ in case 4 the result is

$$\overline{(p)}^m \epsilon^{-at} = (-a)^m \epsilon^{-at} \qquad (12)$$

For integral positive powers of m the bar operator behaves as an ordinary differential operator. If m is a fraction or has a negative value, however, the results are not the same as for the equivalent operational procedure. Purely imaginary terms obtained in this way must be set equal to zero after the final result has been obtained.

Since the bar operators behave in exactly the same manner for fractional values of n as for integral values a "fractional power" differential equation may be set up as easily as an "integral power" differential equation. As an example

$$\overline{(p+a)}^{1/2} i = \epsilon^{bt} t \qquad (13)$$

and the steady-state solution is, as in equation 6

$$i_s = \overline{(p+a)}^{-1/2} \epsilon^{bt} t \qquad (14)$$

It should be pointed out that these "fractional power" differential equations have been set up by analogy with "integral power" differential equations; a purely formal procedure.

Operational Differential Equations

An operational differential equation is to be defined for use in this paper as any one of the equivalent "fractional" or integral power differential equations which may be set up from an operational expression such as

$$i = \frac{p}{(p+a_1)^{n_1}(p+a_2)^{n_2}(p+a_3)^{n_3} \ldots (p+a_k)^{n_k}} \mathbf{1} \qquad (15)$$

No loss in generality will result in the following theory if only three roots are considered since the process may obviously be extended to cover any number of roots. Consider the operational expression

$$i = \frac{p}{(p+a_1)^{n_1}(p+a_2)^{n_2}(p+a_3)^{n_3}} \mathbf{1} \qquad (16)$$

Using the operator in the numerator in turn with each of the root functions in the denominator to form an expression corresponding to equation 7 the three most easily recognizable operational differential equations are

$$\overline{(p+a_2)}^{n_2}\overline{(p+a_3)}^{n_3} i = \frac{\epsilon^{-a_1 t} t^{n_1-1}}{\Gamma(n_1)} \qquad (17a)$$

$$\overline{(p+a_1)}^{n_1}\overline{(p+a_3)}^{n_3} i = \frac{\epsilon^{-a_2 t} t^{n_2-1}}{\Gamma(n_2)} \qquad (17b)$$

$$\overline{(p+a_1)}^{n_1}\overline{(p+a_2)}^{n_2} i = \frac{\epsilon^{-a_3 t} t^{n_3-1}}{\Gamma(n_3)} \qquad (17c)$$

The only restrictions are that $a_1 \neq a_2 \neq a_3$ and n_1, n_2, and n_3 are positive integers, proper or improper fractions. Notice that if the n's are positive integers the bars could be removed from the bar operators on the left-hand sides of equations 17 since they would then be ordinary differential equations any one of which could be represented operationally by (16).

It is now to be proved that in the case of integral positive values of n the unique solution for equations 17 consists of the sum of the particular integrals of (17*a*), (17*b*), and (17*c*). Actually these operations may be extended to fractional values of n but the proof to be given here is not mathematically rigorous. In this case the result usually includes an asymptotic series.

The following expression for $i(t)$ will satisfy equations 17.

$$i = \frac{1}{(p+a_2)^{n_2}(p+a_3)^{n_3}} \frac{\epsilon^{-a_1 t} t^{n_1-1}}{\Gamma(n_1)} + \frac{1}{(p+a_1)^{n_1}(p+a_3)^{n_3}} \frac{\epsilon^{-a_2 t} t^{n_2-1}}{\Gamma(n_2)} + \frac{1}{(p+a_1)^{n_1}(p+a_2)^{n_2}} \frac{\epsilon^{-a_3 t} t^{n_3-1}}{\Gamma(n_3)} \qquad (18)$$

since when (18) is substituted back into, say (17*a*)

$$\overline{(p+a_2)}^{n_2}\overline{(p+a_3)}^{n_3} \times \left[\frac{1}{(p+a_2)^{n_2}(p+a_3)^{n_3}} \frac{\epsilon^{-a_1 t} t^{n_1-1}}{\Gamma(n_1)}\right] + \overline{(p+a_2)}^{n_2}\overline{(p+a_3)}^{n_3} \times \left[\frac{1}{(p+a_1)^{n_1}(p+a_3)^{n_3}} \frac{\epsilon^{-a_2 t} t^{n_2-1}}{\Gamma(n_2)}\right] + \overline{(p+a_2)}^{n_2}\overline{(p+a_3)}^{n_3} \times \left[\frac{1}{(p+a_1)^{n_1}(p+a_2)^{n_2}} \frac{\epsilon^{-a_3 t} t^{n_3-1}}{\Gamma(n_3)}\right] = \frac{\epsilon^{-a_1 t} t^{n_1-1}}{\Gamma(n_1)} \qquad (19)$$

The first term of (19) gives the same time function by (9) while the next two terms become zero since they involve expressions having "equal roots" as in (10). Equivalent results are obtained if (18) is substituted in equations 17*b* and 17*c*. That is, the solution (18) satisfies each of the operational differential equations 17*a*, 17*b*, and 17*c*. In terms of ordinary differential equation theory the first unit of (18) is the particular integral of (17*a*) and the second and third units together form the complementary function with constants of integration already evaluated. Thus the particular integral of one of the equations 17 forms a part of the complementary function for each of the other equations. Since the three original equations are known to have identical operational solutions equation 18 is always a unique evaluation of the operational expression (16). If the n's are positive integers the result (18) is always in a closed form. If (18) is extended to fractional values of n the result usually contains one or more asymptotic series.

The Construction Theorem

The process outlined in the last section can obviously be extended to cover any expression of the form (15) so that the equivalent time function would be given by:

$$i = \sum_{i=1}^{k} \frac{1}{\prod_{j=1\; j\neq i}^{k} (p+a_j)^{n_j}} \frac{\epsilon^{-a_i t} t^{n_i-1}}{\Gamma(n_i)} \qquad (20)$$

The denominator of the bar operator of (20) is the same as that of (15) except that $(p+a_i)^{n_i}$ is omitted.

If the original operational expression (15) had a constant in the numerator instead of the operator p equation 20 would represent the solution for $pi(t)$. The final solution for $i(t)$ could be easily obtained, except in the case where (20) represents an asymptotic series, by operating on the result with p^{-1}. If the original expression had a numerator $F(p)$ consisting of a polynomial in integral powers of p equation 20 could be operated on with $F(p)$ to give the new solution. The integration must be performed before the differentiations or the net result of dividing $F(p)$ by p applied to equation 20.

The result may be given in the form of a "construction theorem" to evaluate operational expressions.

$$\frac{F(p)}{\prod_{i=1}^{k}(p+a_i)^{n_i}} \mathbf{1} = \frac{F(p)}{p} \times \left[\sum_{i=1}^{k} \frac{1}{\prod_{j=1\; j\neq i}^{k} (p+a_j)^{n_j}} \frac{\epsilon^{-a_i t} t^{n_i-1}}{\Gamma(n_i)}\right] \qquad (21)$$

The restrictions for using this theorem are:

1. Functions having equal roots must be combined so that no two roots are identical including zero. The roots may be real or complex. (Two roots which are the same except for the sign are different roots.)

2. $F(p)$ is a polynomial containing only constants or constants multiplied by integral positive powers of p. In cases where the network is impulsive $F(p)$ will contain higher powers of p than the denominator. The result will not, in general, contain the impulsive terms which may be obtained in the usual manner.[5]

3. n_i is a positive integer, positive or negative proper or improper fraction.

4. In cases where the final result contains purely imaginary terms (as, for instance, in the case of $\sqrt{p}\epsilon^{-at}=\sqrt{-a}\epsilon^{-at}$ it is necessary to specify that such terms be dropped after all operations have been performed.

5. The theorem cannot be used in this from when $F(p)/p$ would operate on such terms as t^m where $m \leqq -1$. This restriction is necessary to prevent the "integration" of an asymptotic series.

The construction theorem in this form is more useful than the more complete form to be given which removes the last restriction. An operational expression which contains a fractional power root function in the numerator can usually be cleared of such terms by the usual algebraic procedure.

The last restriction may be removed by writing the left-hand side of equation 21 so as to segregate the zero root function. If $a_k=0$ and $n_k=q$ then

$$\frac{F(p)}{p^q\prod_{i=1}^{k-1}(p+a_i)^{n_i}}\mathbf{1}=$$

$$F(p)\left[\frac{p}{p^{q+1}\prod_{i=1}^{k-1}(p+a_i)^{n_i}}\right]\mathbf{1}=$$

$$F(p)\left\{\sum_{i=1}^{k-1}\frac{1}{p^{q+1}\prod_{j=1\,j\neq i}^{k-1}(p+a_j)^{n_j}}\frac{\epsilon^{-a_it}t^{n_i-1}}{\Gamma(n_i)}+\frac{1}{\prod_{i=1}^{k-1}(p+a_i)^{n_i}}\frac{t^q}{\Gamma(q+1)}\right\} \quad (22)$$

q is a positive integer or fraction. In this case $a_i \neq 0$. Multiplying both numerator and denominator by p arranges the expression inside the square brackets in the form of equation 15 so that the solution is given by the last line which is equivalent to equation 21. This final form of the construction theorem appears to be perfectly general under the limitations imposed by the first four restrictions. Only differentiations are involved which may be performed on any time function which may appear.

Illustrative Example

Evaluate the operational expression

$$i=\frac{p+c}{(p+a)(p+b)}\mathbf{1} \quad (23)$$

Using the first form of the construction theorem (21) $F(p)=p+c$ and (23) can be written

$$i=\left[\frac{p+c}{p}\right]\left[\frac{p}{(p+a)(p+b)}\mathbf{1}\right] \quad (24a)$$

Two of the fundamental forms (7) may be recognized in (24*a*)

$$i=\left[1+\frac{c}{p}\right]\left[\frac{1}{(p+b)}\left\{\frac{p}{(p+a)}\mathbf{1}\right\}+\frac{1}{(p+a)}\left\{\frac{p}{(p+b)}\mathbf{1}\right\}\right] \quad (24b)$$

From (7)

$$\frac{p}{(p+a)}\mathbf{1}=\epsilon^{-at}$$

and

$$\frac{p}{(p+b)}\mathbf{1}=\epsilon^{-bt}$$

and (24*b*) becomes

$$i=\left[1+\frac{c}{p}\right]\left[\frac{1}{(p+b)}\epsilon^{-at}+\frac{1}{(p+a)}\epsilon^{-bt}\right] \quad (24c)$$

Shifting the exponentials

$$i=\left[1+\frac{c}{p}\right]\left[\epsilon^{-at}\frac{1}{b-a}+\epsilon^{-bt}\frac{1}{a-b}\right] \quad (24d)$$

Performing the integration and rearranging the final result is

$$i=\frac{c}{ab}+\frac{1}{b-a}\left[\left(\frac{a-c}{a}\right)\epsilon^{-at}+\left(\frac{c-b}{b}\right)\epsilon^{-bt}\right] \quad (24e)$$

Cable With Terminal Inductance

One of the interesting problems originally solved by Heaviside[6] is the case of a unit voltage applied to an infinite cable with terminal inductance. The operational expression giving the voltage at the head end of the cable is of the form

$$V_0=\frac{1}{1+(bp)^{3/2}}\mathbf{1} \quad (25)$$

where b is a positive constant. Write this as

$$V_0=\frac{1-(bp)^{3/2}}{1-(bp)^3}\mathbf{1}$$

$$=\frac{1}{b^3}\left\{b^{3/2}p\times\left[\frac{p}{\sqrt{p}\left(p-\frac{1}{b}\right)\left(p+\frac{1-j\sqrt{3}}{2b}\right)\left(p+\frac{1+j\sqrt{3}}{2b}\right)}\right]-\frac{1}{p}\times\left[\frac{p}{\left(p-\frac{1}{b}\right)\left(p+\frac{1-j\sqrt{3}}{2b}\right)\left(p+\frac{1+j\sqrt{3}}{2b}\right)}\right]\right\}\mathbf{1} \quad (26)$$

The construction theorem may now be used for both terms.

$$V_0=b^{3/2}\left[\frac{p}{\sqrt{p}\left(p-\frac{1}{b}\right)\left(p+\frac{1-j\sqrt{3}}{2b}\right)}\times\epsilon^{-\left(\frac{1+j\sqrt{3}}{2b}\right)t}+\frac{p}{\sqrt{p}\left(p-\frac{1}{b}\right)\left(p+\frac{1+j\sqrt{3}}{2b}\right)}\epsilon^{-\left(\frac{1-j\sqrt{3}}{2b}\right)t}+\frac{p}{\sqrt{p}\left(p+\frac{1+j\sqrt{3}}{2b}\right)\left(p+\frac{1-j\sqrt{3}}{2b}\right)}\epsilon^{\frac{1}{b}t}\right]-$$

$$\frac{b^{3/2}}{1-(bp)^3}\left\{-\frac{1}{2\sqrt{\pi}}t^{-3/2}\right\}-$$

$$\frac{1}{b^3p}\left[\frac{1}{\left(p-\frac{1}{b}\right)\left(p+\frac{1-j\sqrt{3}}{2b}\right)}\epsilon^{-\left(\frac{1+j\sqrt{3}}{2b}\right)t}+\frac{1}{\left(p-\frac{1}{b}\right)\left(p+\frac{1+j\sqrt{3}}{2b}\right)}\epsilon^{-\left(\frac{1-j\sqrt{3}}{2b}\right)t}+\frac{1}{\left(p+\frac{1+j\sqrt{3}}{2b}\right)\left(p+\frac{1-j\sqrt{3}}{2b}\right)}\epsilon^{\frac{1}{b}t}\right] \quad (27)$$

When the indicated operations of (27) are carried through and the terms collected

$$V_0=1-\frac{4}{3}\epsilon^{-\frac{1}{2b}t}\cos\frac{\sqrt{3}t}{2b}+\frac{1}{2\sqrt{\pi}}\left(\frac{b}{t}\right)^{3/2}\times\left[1-1\cdot3\cdot5\cdot7\left(\frac{b}{2t}\right)^3+1\cdot3\cdot5\cdot7\cdot9\cdot11\cdot13\left(\frac{b}{2t}\right)^6\ldots\ldots\right] \quad (28)$$

The final result[5] as given by equation 28 checks that of Heaviside obtained by "advanced ideas" not stated.

This example is sometimes given as a case in which "Heaviside's method" fails, although he obtained the correct solution. As Heaviside himself made no general statement of his methods it might be inferred that he was at least partially aware of the relationship between his own work and ordinary differential equations. He makes the statement that,[7] "sometimes a series of differentiations may equivalently replace a series of integrations." It is unfortunate that he did not develop this relationship more fully.

Sinusoidal Electromotive Force Applied to an Infinite Cable

Another well-known problem is to find the entering current when a sinusoidal electromotive force is applied to an infinite cable. The operational equation is of the form

$$i=\sqrt{p}\sin\omega t\mathbf{1} \quad (29)$$

which is a combination of

$$\sqrt{p}\,1=\frac{1}{\sqrt{\pi t}}$$

and

$$\frac{\omega p}{p^2+\omega^2}1=\sin\omega t$$

Using the construction theorem

$$i=\omega p\left[\frac{1}{\sqrt{p}\,(p-j\omega)}\epsilon^{-j\omega t}+\frac{1}{\sqrt{p}\,(p+j\omega)}\epsilon^{-j\omega t}+\frac{1}{\omega^2+p^2}\frac{1}{\sqrt{\pi t}}\right] \quad (30)$$

and the final result is:

$$i=\sqrt{\frac{\omega}{2}}(\sin\omega t+\cos\omega t)-\frac{1}{\sqrt{\pi t}}\left(\frac{1}{(2\omega t)}-\frac{1\cdot3\cdot5}{(2\omega t)^3}+\frac{1\cdot3\cdot5\cdot7\cdot9}{(2\omega t)^5}\cdots\right) \quad (31)$$

One of the advantages of using this method of attack on operational expressions is the ease of checking the result obtained. Equation 29 may be set up in two equivalent operational differential equations:

$$(p^2+\omega^2)i=\frac{\omega p^2}{\sqrt{p}}1=-\frac{\omega}{2\sqrt{\pi}}t^{-3/2} \quad (32)$$

and

$$\sqrt{p}\,i=\frac{\omega p^2}{p^2+\omega^2}1=\omega\cos\omega t \quad (33)$$

If (31) is substituted in (32) the first term of (31) becomes zero since the second derivative of this term is the term itself multiplied by $-\omega^2$. All of the series terms will cancel out except the term on the right of (32). If (31) is substituted in (33) the first term of (31) becomes $\omega\cos\omega t$ and the odd-half power terms of (31) are reduced to zero as in equation 10.

Conclusions

The construction theorem which has been developed is not always the most direct method of solving every operational expression for which it is applicable. In the case of fractional power root functions the result will, in general, contain one or more asymptotic series. In particular if a certain solution is desired in terms of a convergent series of fractional powers of the variable t the result must be obtained by some other method. Several of the more obvious advantages in using the theorem may be listed as follows:

(*a*). The theorem brings out the relationship between ordinary differential equations and Heaviside's calculus. This results in the concept of "equivalent operational differential equations" which is far more important than the development of a fixed routine for the solution of individual operational expressions.

(*b*). The theorem involves no exceptions or complicated tests which must be applied before it is used.

(*c*). The necessary mathematical manipulations are easily learned since the main prerequisites are a knowledge of the binomial theorem and the ability to differentiate simple functions of time.

(*d*). Operational expressions which might otherwise be evaluated by Heaviside's expansion theorem can, more often than not, be evaluated by inspection.

(*e*). The final result may be easily checked by substituting results into the original equations.

Outline for a Rigorous Mathematical Proof of the Construction Theorem

To prove the construction theorem it is necessary and sufficient to show that the operations indicated by the key equation 18 can be substantiated by an equivalent procedure using the Bromwich[8] contour integral in the complex plane (*a*) for integral positive values of n and (*b*) for fractional positive values of n.

The symbols and definitions to be used in this discussion are given by reference 8.

Equation 16 becomes

$$i=\frac{1}{2\pi j}\int_{-j\infty+c}^{+j\infty+c}\times\frac{\epsilon^{zt}}{(z+a_1)^{n_1}(z+a_2)^{n_2}(z+a_3)^{n_3}}dz \quad (34)$$

1. Bromwich contour integral 1 is equivalent to Bromwich contour integral 2 for (34) since for large values of z the finite values of a may be set equal to zero and the proof is given by reference 8, pages 58–61.

2. The final result for (34) can now be obtained by taking the sum of the contributions of the individual roots along Bromwich integral 2. To evaluate the contribution of one root, say $-a_1$, first change the variable to $z'=z+a_1$. This is equivalent to the shifting operation indicated for ϵ^{-a_1t} in equation 18. Expand the bracket terms containing a_2 and a_3 by the binomial theorem in ascending powers of z' separately and then perform the indicated multiplications. The resulting series is analytic for values of z' less than the least radius of convergence of the two original series but not for large values of z'.

The contribution of each root is now in the form of a series of terms of the type

$$\frac{\epsilon^{-a_1t}}{2\pi j}\int_{Br_2}\frac{\epsilon^{z't}}{z'^{r+1}}dz'=\frac{\epsilon^{-a_1t}t^r}{\Gamma(1+r)} \quad (35)$$

good for all values of r. Proof for (35) is indicated on pages 76–8 of reference 8. Term by term this can be shown to be equivalent to the differentiating process indicated by the first unit of equation 18.

4. In the case of integral positive values of n the contribution of the two straight lines of Bromwich integral 2 for any particular root in an expression such as (34) is zero, so that (35) includes only the integral around the circle whose radius can be made as small as necessary to make the series expansion convergent. For integral powers of n equation 18 always gives the evaluation of expression 16 in closed form.

5. In the case of fractional powers of n the series expansions do not represent the original functions beyond the least radius of convergence of the two series. The expression to be integrated along the straight lines of Bromwich integral 2 does not converge except close to the new origin. However, for large values of t most of the integral is obtained in the neighborhood of the origin, a process which usually results in an asymptotic series.

In integrating along Bromwich integral 2 for fractional powers of n it sometimes happens that one root appears in the "tail" of the integration path for the other. In this case the weaker root may be dropped for an asymptotic solution. This is equivalent to the restriction 4 for the construction theorem. The contributions obtained in this way coincide with those given by the construction theorem.

References

1. ÜBER EINE FORMEL VON HEAVISIDE ZUR BERECHNUNG VON EINSCHALTVORGÄNGE, **K. W. Wagner.** *Archiv. f. Elek.*, volume 4, 1916, pages 159–93.

2. THE CAUCHY-HEAVISIDE EXPANSION FORMULA AND THE BOLTZMANN-HOPKINSON PRINCIPLE OF SUPERPOSITION, **F. D. Murnaghan.** American Mathematical Society Bulletin, volume 33, 1927, pages 81–9.

3. ON A GENERAL EXPANSION THEOREM FOR THE TRANSIENT OSCILLATIONS OF A CONNECTED SYSTEM, **John R. Carsen.** *Physical Review*, volume 10, series 2 (1917), pages 217–25.

4. A GENERALIZED INFINITE INTEGRAL THEOREM, **M. G. Malti.** AIEE TRANSACTIONS, volume 54, 1935 (November section), pages 1222–7.

5. OPERATIONAL CIRCUIT ANALYSIS (a book), **V. Bush.** John Wiley and Sons, 1937.

6. ELECTROMAGNETIC THEORY (a book), **Oliver Heaviside.** London, 1899, page 42.

7. ELECTROMAGNETIC THEORY (a book), **Oliver Heaviside.** London, 1899, page 303.

8. COMPLEX VARIABLE AND OPERATIONAL CALCULUS WITH TECHNICAL APPLICATIONS (a book), **N. W. McLachlan.** Cambridge University Press, 1939.

A Study of Sound Levels of Transformers

H. FAHNOE
ASSOCIATE AIEE

I. Introduction

MUCH has been accomplished in the past few years in understanding the problem of transformer noise. It has been definitely established that magnetostriction discovered by Joule in 1842 is the principal source of transformer noise. The various harmonic vibrations generated in the core by magnetostriction have been analyzed. Methods of calculating sound levels in terms of the standards prepared by the American Standards Association have been developed. A large number of modes in which different core structures may vibrate have been determined experimentally and analytically. As a result, methods for determining the correct design proportions of the core have been developed so that the natural modes of vibration may not coincide with the harmonic vibrations generated by magnetostriction. These methods have been successfully applied to actual designs of transformers including the largest ratings.

This paper will serve as a partial report of the research and experimental work which has been accomplished in the laboratories of the company with which the writer is associated.

II. Transformer Noise

Until recent years it had been assumed generally that the main cause of transformer noise was the magnetic pull between the laminations at their joints. In order to determine the correctness of this assumption, an investigation was started in 1932 by experimenting with an iron ring without gaps or joints. This ring was made up of laminations, 18 inches outside diameter, $8^1/_2$ inches inside diameter, built up to five inches. The laminations were clamped between heavy maple blocks; they could be energized by means of one turn through the center opening of the ring or more turns wound uniformly around the ring. When energized with alternating current, the ring emitted the characteristic "hum" heard from any transformer as soon as it is energized. The "hum" or noise increased as the flux density was increased. With a sine wave of voltage applied to the exciting winding and with a fixed number of ampere turns, the noise level was the same whether the ring was energized by means of one or several turns.

From these tests it was apparent that the joints in the core and mechanical dissymmetries between the energizing winding and the core could not account for the noise emitted from a well-built transformer.

In measuring the vibrations parallel with the plane of the laminations at different points around the periphery of the ring, it was found that the ring as a whole expanded with a very pronounced vibration of twice the applied frequency. These peripheral vibrations were all in phase or, in other words, the diameter of the ring was pulsating with an amplitude which was found to depend upon the flux density in the ring. It was only possible to explain these vibrations as a phenomenon of magnetostriction. The unit elongations calculated from these vibrations were of the expected order based on a knowledge of the magnetostriction.

Typical vibration measurements at the fundamental vibrational frequency taken on a rectangular core are shown in figure 1. It will be noticed that the deflections at the different flux densities are approximately proportional to the length of the various core members. The deflections shown occur simultaneously, that is, they are in phase. Vibrations as symmetrical as shown in figure 1[1] are obtained only when the laminations are straight and uniformly clamped. By changing the method of clamping, the deflections along a certain member may change considerably. The core may, for instance, vibrate as shown in figure 2.

The 120-cycle sound intensities calculated from the deflections shown in figures 1 and 2 correspond closely to those measured with a sound level meter with the microphone located approximately one-half inch from the core. The 120-cycle sound level of this core is, therefore, practically entirely accounted for by magnetostriction. The relation between magnetostriction and induction (B) is generally such that the core vibrates also at harmonically related higher frequencies. Both odd and even harmonic vibrations are produced. In figure 3 is shown such vibrations measured at one end of a large rectangular core. With the apparatus available, it was possible to measure vibrations up to the tenth harmonic. In this figure the vibrations are plotted as velocities. The amplitudes of the vibrations are in inverse ratio to the frequencies.

The number and magnitude of these higher harmonic vibrations depend upon the nature of the steel, the flux density, and the linear dimensions of the core. Any particular grade of steel has, therefore, a characteristic noise spectrum for each flux density. Such a spectrum is shown in figure 4 for steel at a flux density $B = 15{,}000$ gausses. The ordinates are plotted in decibels.

The core of any transformer is in itself a structure which may vibrate in many modes, depending upon its degree of freedom. When the laminations of a core as shown in figure 1 are clamped between heavy end frames, the core is practically free to swing only in a direction parallel with the plane of the laminations. A large number of modes of vibration are possible in this plane, each mode occurring at a certain frequency. This form of core and end frame construction is common in shell-type transformers. If the core is not clamped between heavy end frames and is standing upright as in core-type transformers, it has several degrees of freedom, that is, it may vibrate in several planes, and in numerous modes in each plane. In either case, it is possible that the core structure may be in mechanical resonance with one or more of the frequencies generated in the core due to magnetostriction. The amplitudes of vibration at such frequencies will, therefore, be in excess of the forced vibrations caused by magnetostriction.

In figure 5 are shown some typical vibration measurements made on a shell-type transformer which was energized at a constant induction at different frequencies. In this test the core was not clamped tight, and the bottom and top end frames were, therefore, more or less loosely coupled with the core. The vibrations were measured at five points along the vertical center line of the long side as shown.

The upper end frame showed resonance at approximately 100 cycles (figure 5, point 5a); above 130 cycles it was driven

Paper 41-53, recommended by the AIEE committee on electrical machinery, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 22, 1940; made available for preprinting December 12, 1940.

H. FAHNOE is design engineer for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

The author wishes to thank C. R. Hanna, W. O. Osbon, S. J. Mikina, and J. G. Baker of Westinghouse research laboratories, and H. V. Putman, S. Bennon, and F. J. Vogel of Westinghouse transformer engineering department for the many helpful suggestions received during this investigation.

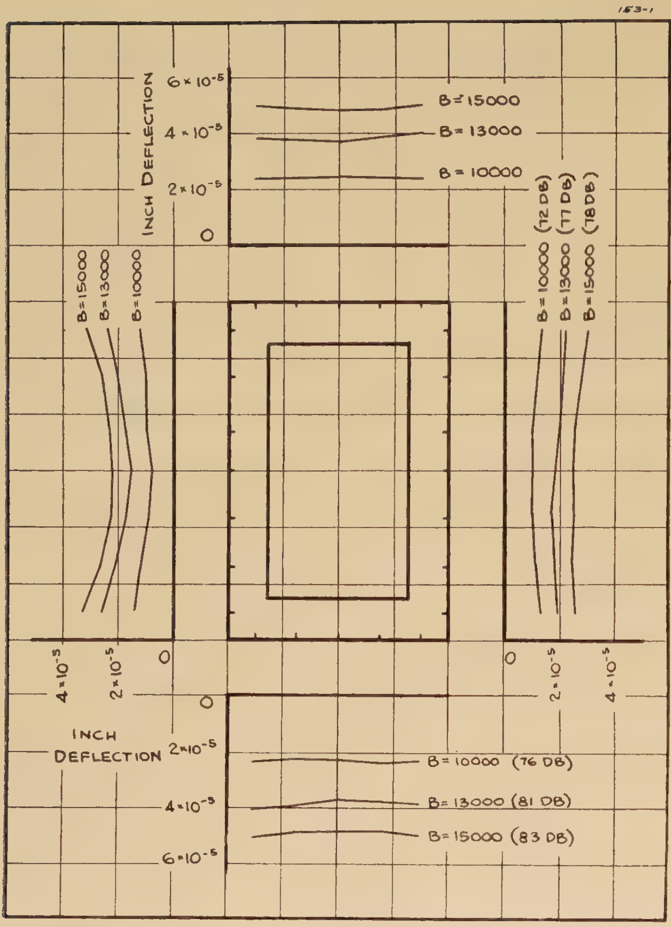


Figure 1. 120-cycle core deflections parallel with the plane of laminations at 60-cycle excitation

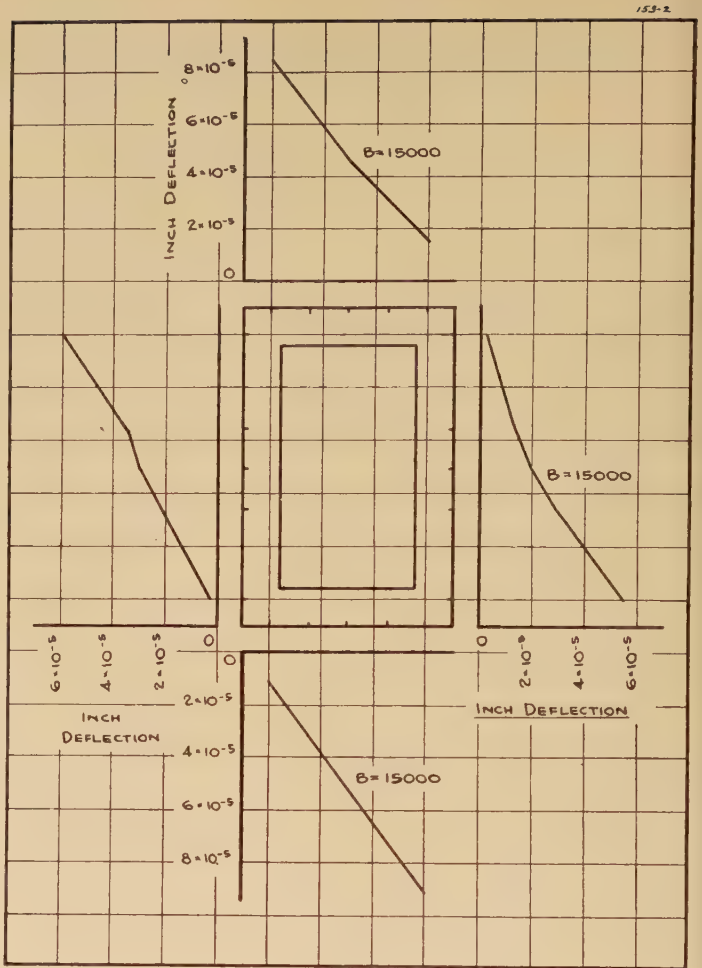


Figure 2. 120-cycle core deflections parallel with the plane of laminations at 60-cycle excitation

by the core which was in resonance at 136 cycles as shown in figure 5 (points 5*b*, 5*c*, and 5*d*). The calculated deflection of the core, due to magnetostriction, was approximately 0.05 mil double amplitude, and it will be noted that at 136 cycles, the core vibrated with an amplitude 16 times that corresponding to the magnetostriction. This means that the noise level on this side of the core was approximately 24 decibels higher than normal at this particular flux density. From figure 5, point 5*e*, it will be seen that the lower end frame is in resonance at approximately 102 cycles and starts to be driven by the core when the frequency was above 132 cycles.

By increasing the coupling between the core and the end frames, that is, by clamping the structures together, the vibrations in the range from 100 to 130 cycles will be somewhat increased. It is, therefore, evident that it is desirable that the core and the end frames have as nearly as possible the same natural frequencies. It will also be noted from these figures, that the band of partial resonance extends about 20 to 25 cycles on either side of the resonance frequency.

The mode of vibration at the resonance frequency of 136 cycles was determined by the use of two equally sensitive vibration pickups connected in series so that their voltages add. The mode was of the nature shown in figure 6*a*. Two of the opposite sides are deflecting outward at the instant the other two sides are deflecting inward. This is the lowest possible mode for a box structure which has practically only one degree of freedom. The exciting frequency of the supply at the 136 cycles vibrational frequency was 68 cycles. The same mode would have occurred at 136 cycles if the core had been energized at 34 cycles. In this case, the core would have been in resonance with the second harmonic vibration due to magnetostriction. But, because of clamping in the core and since for this particular steel the second harmonic driving force is less than for the fundamental, the amplitude of the 136-cycle vibration would have been less.

If the frequency had been further increased above 136 cycles, another resonance point would have occurred at approximately 292 cycles. The mode of vibration at this frequency would have been as shown in figure 6*b*. Here all four sides are simultaneously deflecting outward. This mode requires a rather rigid joint at the corners and is, therefore, not always excited.

At still higher frequencies more complicated modes are excited. The different sides will then vibrate in odd number of half cycles.

Figure 7 shows the consecutive modes of vibration which occur in a three-phase shell-type transformer.

The frequencies of these modes depend upon the dimensions of the core and the modulus of elasticity of the steel used. They may be calculated from a formula of the form

$$f = K\frac{W}{l_1^2} \qquad (1)$$

where

K = a function of the ratio l_1/l_2 and the modulus of elasticity
W = width of the laminations
l_1 = mean length of the longest side
l_2 = mean length of the short side

From experimental data it has been found advisable to design the core of

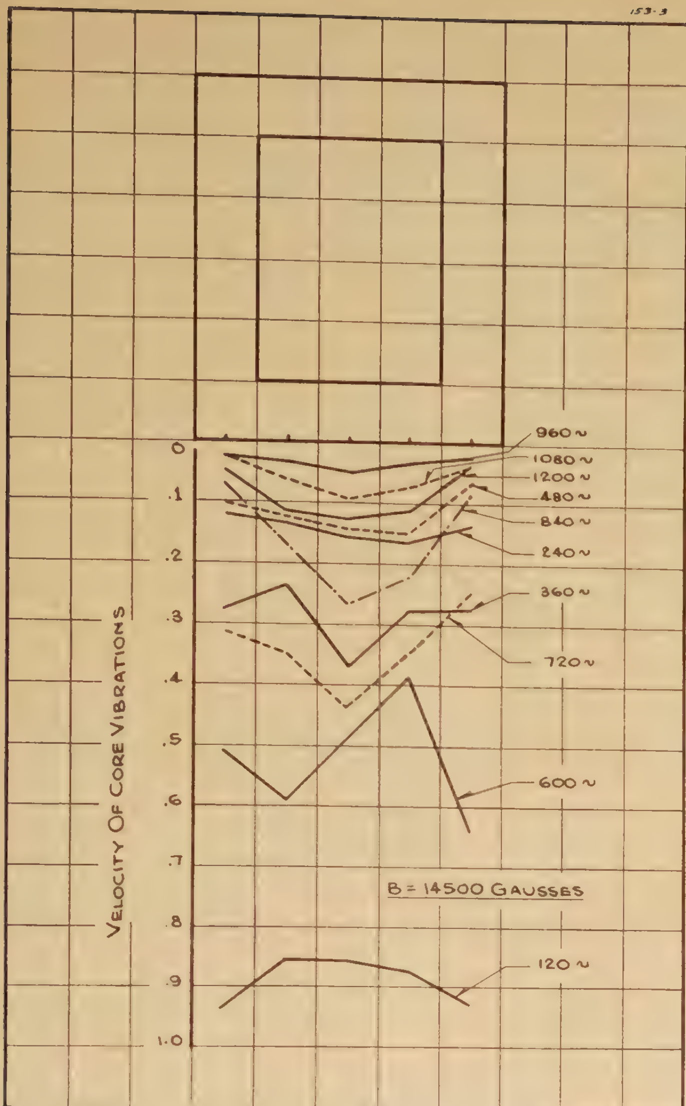


Figure 3. Velocity of core vibrations parallel with the plane of laminations at 60-cycle excitation

such dimensions that its natural frequencies are separated approximately 25 to 30 cycles from any of the harmonic frequencies generated in the core by the excitation frequency.

The end frames for shell-type transformers are more or less complicated box structures and their natural frequencies may be determined along the same lines as indicated for the core.

As previously stated, the core-type transformer as usually constructed is free to vibrate in several planes. The modes of vibration parallel with the plane of the laminations may be of the same nature as the modes described for box structures, and may be determined by means of equation 1. Such a mode for a single-phase core-type transformer is shown in figure 8. In this particular core the mechanical resonance frequency was 294 cycles. This mode would, therefore, not be excited by any of the frequencies generated in the core at 60-cycle excitation. The amplitudes in the center of the legs are approximately 19 times that corresponding to the magnetostriction at this particular flux density. On the other hand, the upright core represents two or more columns with a load at their ends which are free to vibrate in planes principally parallel and perpendicular to the laminations. The core may, therefore, also vibrate in modes as shown in figures 9 and 10, in a plane parallel with the laminations or in modes as shown in figure 11, in a plane perpendicular to the plane of laminations. In figure 11, the elongations of the legs in the direction of their length are restrained by inertia forces due to the presence of large masses on their ends, and they bow out. Some of these modes are rather critical and difficult to duplicate under apparently similar conditions. They are apparently influenced by the mounting of the core on its foundation.

With resonance eliminated, by proper selection of the core dimensions, the amplitude (A) at the fundamental vibrational frequency of any member of the core may be calculated from the magnetostriction characteristics of the steel. For a core member of length (L), the amplitude at each end equals

$$A = \frac{\Delta L}{L} \times \frac{L}{2} \qquad (2)$$

where $\Delta L/L$ = elongation per unit length due to magnetostriction. The corresponding physical intensity of the sound wave may be calculated by means of the fundamental equation for a plane sound wave, emitted from a large plane vibrating surface.

The maximum excess pressure in such a wave equals

$$P = V \times d_0 \times A \times 2\pi f \qquad (3)$$

where V = velocity of wave, d_0 = mean density, A = maximum amplitude of the wave, and f = frequency.

When V is in centimeters per second

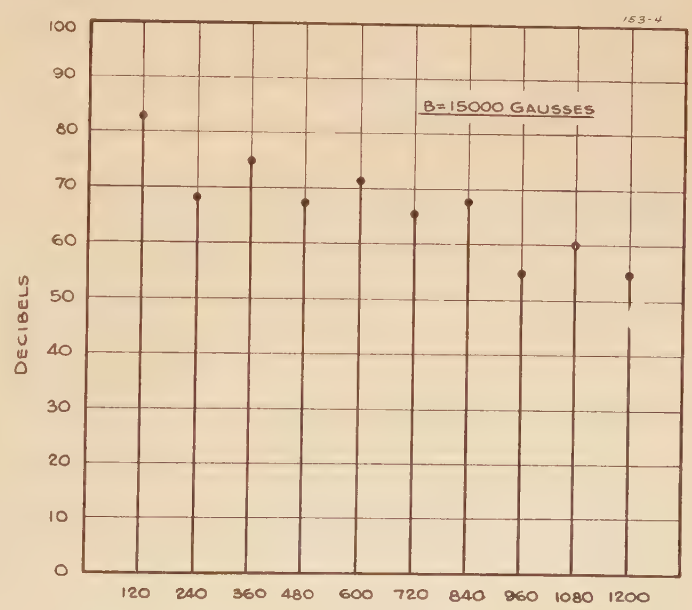


Figure 4. Noise spectrum of transformer steel at 60-cycle excitation

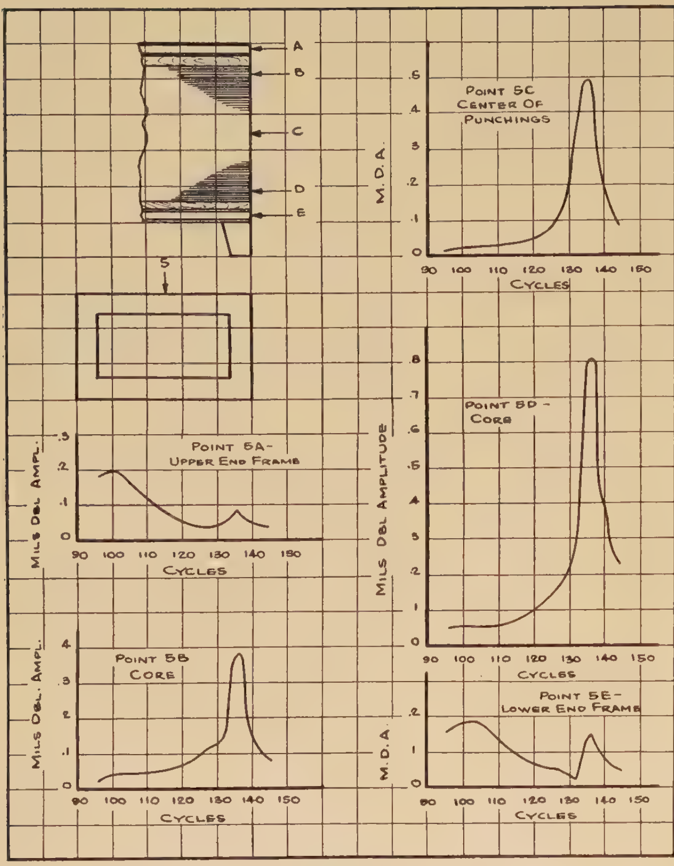


Figure 5. Resonance curve of shell-type transformer core. Core not clamped

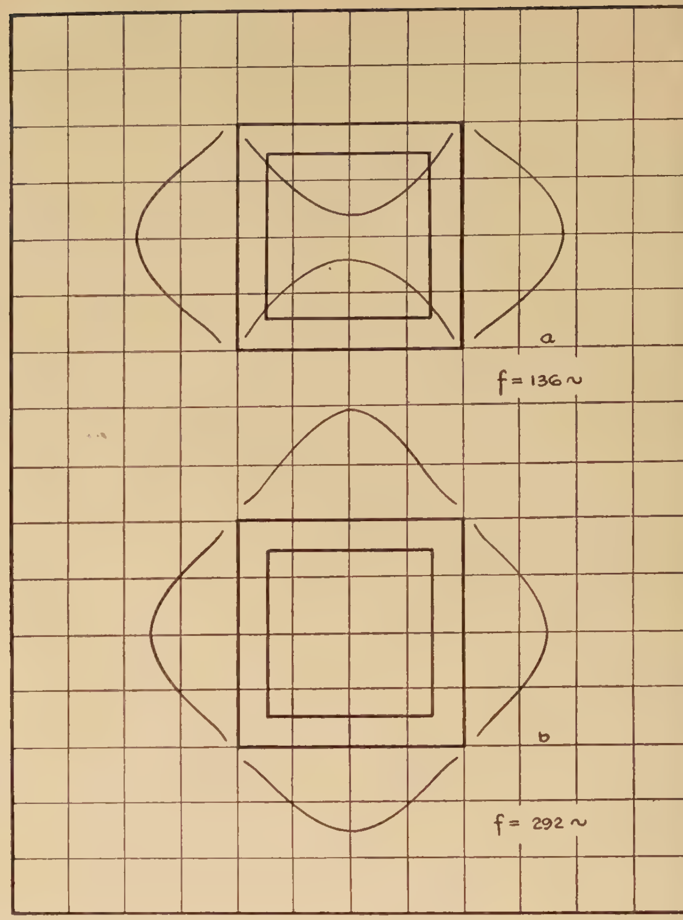


Figure 6. Mode of vibrations of rectangular cores

(=33,300 for air), d_0 in gram per cubic centimeter (=0.0012 for air), the rms excess sound pressure in dynes per square centimeter equals

$$P_{\text{rms}} = 177 \times A_{\text{cm}} \times f \tag{4}$$

or if A is in inches

$$P_{\text{rms}} = 452 \times A_{\text{in}} \times f \tag{5}$$

The average energy density of such an acoustic wave equals

$$W = 2\pi^2 A^2 f^2 d_0$$
$$= \frac{P_{\text{rms}}^2}{d_0 V^2} \text{ gram per cubic centimeter} \tag{6}$$

and the intensity or average rate of flow of energy per unit area perpendicular to the direction of propagation, equals

$$I = W \times V = \frac{P_{\text{rms}}^2}{d_0 V} \text{ ergs per second per square centimeter} \tag{7}$$

For a wave in air

$$I = 2.5 \times 10^{-9} \times P_{\text{rms}}^2 \text{ watts per square centimeter} \tag{8}$$

In sound terminology, the decibel expresses the ratio of any given sound intensity (I) to the reference sound intensity. The standard reference level for intensity level comparisons is 10^{-16} watts per square centimeter. The decibel is defined as

$$\text{db} = 10 \log_{10} \frac{I}{10^{-16}} \tag{9}$$

The decibel also expresses the ratio of any given sound level pressure (P) to the reference pressure. The standard reference level for pressure level comparisons is 0.0002 dyne per square centimeter. Since the intensity is proportional to the square of the pressure, we have

$$\text{db} = 20 \log_{10} \frac{P}{0.0002} \tag{10}$$

The physical intensity, in decibels, of the sound wave emitted at the fundamental vibrational frequency of the core may, therefore, be determined by substituting in (9) or (10) the values for I or P determined from (8) or (5).

As previously stated, a large number of harmonic vibrations are produced in the core due to magnetostriction. The arithmetical sum of the intensities, of the sound waves caused by these vibrations, for ordinary grades of silicon steel, is in general not more than one decibel in excess of the sound intensity of the fundamental sound wave. The sound intensity measured with a sound level meter with a "flat" frequency response will, therefore, approximately equal the intensity of the fundamental sound wave calculated as indicated above. This value will be designated as db_F. The intensities of the individual harmonics may also be weighted according to any of the recognized standard equal loudness contours for pure tones. For transformers it is the standard practice to refer all sound level measurements to the 40-decibel equal loudness contour. This value may be measured directly with a modern sound level meter, and will be designated as db_{40}.

The difference between the sound measured with the "flat" and the 40-decibel frequency response will give a fair indication of the quality or the harmonic components of the sound measured. This difference may, therefore, be designated "harmonic index" (h.i.), or

$$\text{h.i.} = \text{db}_F - \text{db}_{40} \tag{11}$$

Where the h.i. is large it is an indication that the sound contains large components of low-frequency tones, whereas a small h.i. indicates that higher frequency tones are predominating.

The harmonic index of a certain grade

of steel as a function of the induction is shown in figure 12.

The sound level of the core may now be estimated as follows. The amplitude of the core vibrations at fundamental vibrational frequency is determined from the magnetostriction of the steel, the length of the magnetic circuit involved, and the flux density at which the core is worked. From this amplitude the excess pressure of the sound wave in dynes per square centimeter and the corresponding decibel sound intensity is calculated (db_F). In order to obtain the sound level corresponding to the 40-decibel frequency response, the "harmonic index" corresponding to the flux density at which the core is worked should be subtracted from the above sound intensity, or the sound level of the core is approximately

$$db = db_F - h.i. \tag{12}$$

Numerous tests on different cores and at different flux densities have shown close agreement between the calculated and measured sound levels. However, because of the large number of assumptions made in these calculations and since these assumptions are only approximations, caution should be made in their use. The method of calculation would, for instance, have to be changed in case the steel has a sound spectrum widely different from that commonly used in present transformers.

It is well known that the load currents give rise to magnetic forces around and between the high- and low-voltage coils of a transformer. These forces will produce vibrations of the coils with double the applied frequency. Higher harmonics are in general not produced. The construction of the coils is in general such that they are relatively poor sound radiators. In a properly designed transformer, the vibrations produced by the coils will, therefore, contribute relatively little to the total noise level of the transformer when measured on the 40-decibel frequency response.

When the core and coils are placed in their tank and immersed in oil, their motion is transmitted through the oil to the tank wall and from there emitted as sound waves to the surrounding air. For most of the vibrations generated in the core the oil may be considered an incompressible fluid. This means that the oil will act as an added mass to the tank wall and only a small amount of energy at the higher frequencies will be transmitted through the oil and the tank wall as a true wave motion. The tank wall, bottom, and cover are, therefore, forced to vibrate as diaphragms. In general, these diaphragmatic vibrations are not produced in the tank wall as a whole, at any frequency. The tank is a relatively complex structure. Radiators, potheads, switch cabinets, etc., may be welded to the tank wall. Its surface is, therefore, broken up in a large number of smaller areas, vibrating with different phases and magnitudes. Provided no parts of the tank surface are in resonance with any of the exciting frequencies produced by the core, the resulting vibrations are forced. Their magnitudes may be smaller than that of the core. The reduction depends upon the height and thickness of the tank wall, the distance between the core and tank wall, the relative density of the material of the tank wall and that of the oil.

Methods for predetermining the amount of attenuation are being studied, but the problem is very complex and empirical constants are used at present.

Assuming the oil to act as an incompressible fluid, the average "harmonic index" of the tank wall vibrations will correspond closely to the average "harmonic index" observed on the core itself. For example, on one of the largest transformers built, the average "harmonic index" of the core was 9.1 decibels when measured out of its tank. When the transformer was placed in its tank, the average h.i. measured 9.6 decibels, indicating relatively little change in the harmonic vibrations of the core and the tank wall. A large number of similar

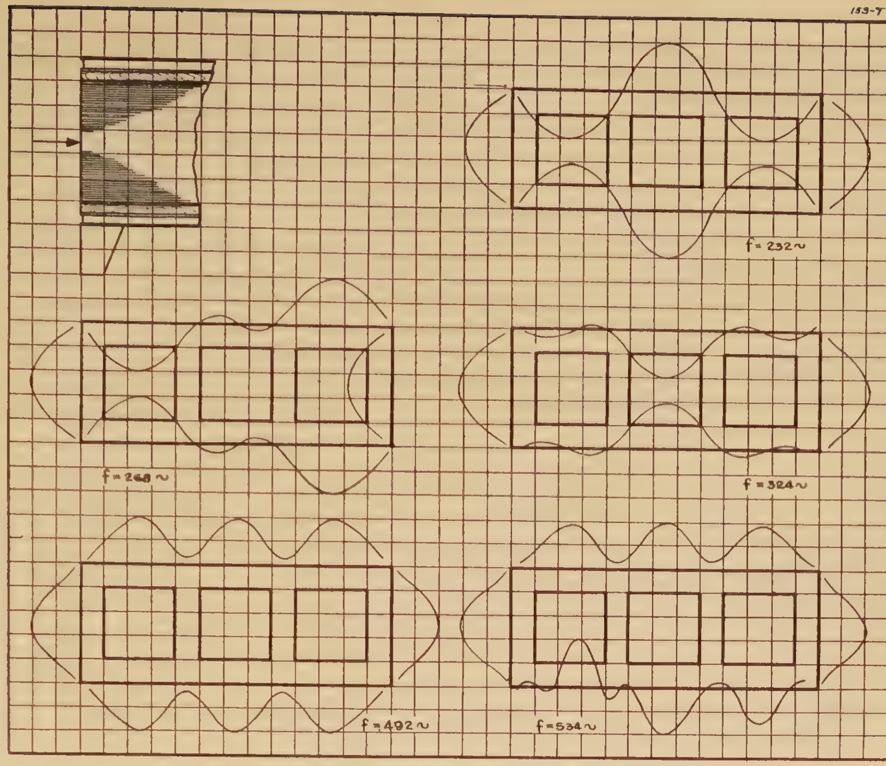


Figure 7. Phase relations of vibrations measured on center line of three-phase shell-type transformer

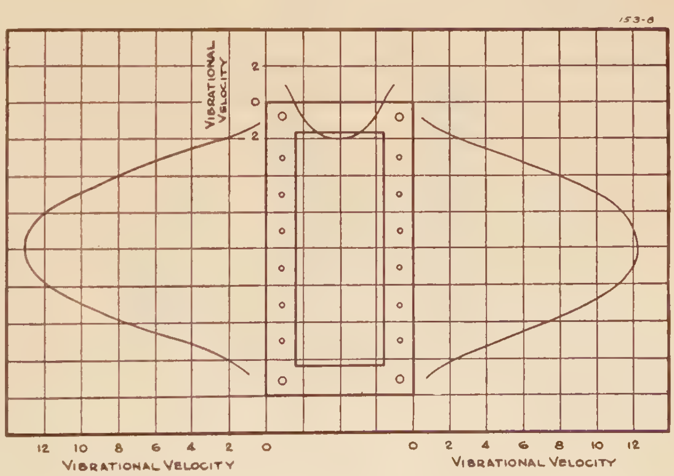


Figure 8. Magnitude and phase relations of 294-cycle vibrations parallel to the plane of laminations

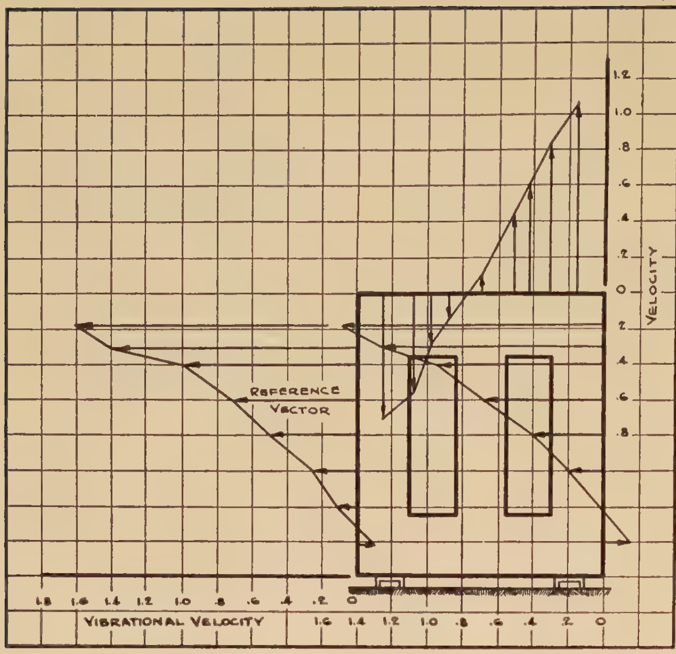
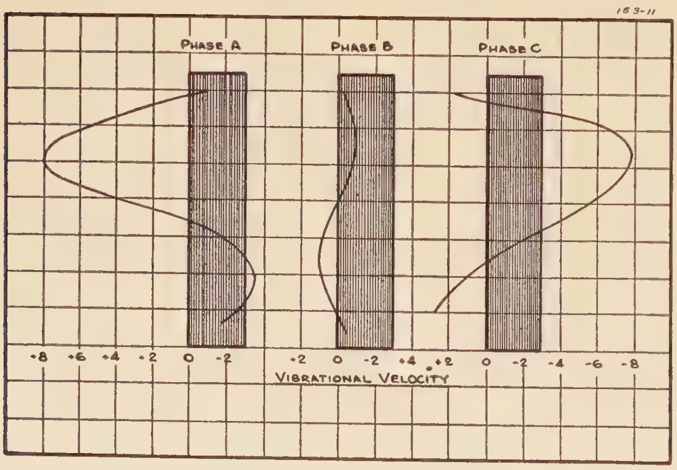


Figure 9. Core vibrations at 124-cycle vibrational frequency in a plane parallel with the laminations of a three-phase core

tests on a variety of transformers have given similar results. Where a large discrepancy has been observed it has been an indication of resonance in some parts of the tank wall or improper mounting of the transformer in its tank. The tank wall or segments of the tank wall may have free vibrations of their own at a large number of frequencies and modes. If such vibrations are in resonance with any of the core vibrations, they may in general be reduced by relatively simple means, such as braces anchored at suitable points.

Cooling tubes, radiators, etc., may complicate the motions of the tank wall, but in themselves these parts are relatively poor sound radiators for sounds of the frequencies involved in transformer operation. They contribute, therefore, relatively little to the total sound level of the transformer.

Figure 11. Phase relations of 116-cycle vibrations perpendicular to the plane of laminations of a three-phase core



The vibrations of the tank may produce two kinds of sound, when the transformer is installed in its final location:

1. A direct air-borne sound, radiated from the tank wall, cover, radiators, etc.

2. A sound transmitted through the transformer foundation to the wall or other structural work of the building in or near where the transformer is installed.

Of these two sources, number 1 is, in general, the most important and also the most difficult to insulate against. Air-borne sounds must be "sealed in." This may be accomplished by means of sound-absorbing walls surrounding the transformer, but this is a remedy which seldom can be used.

Source number 2 may be of importance in certain installations where large areas may be set in vibration by transmission of vibrations through materials like steel or concrete which transmit vibrations much more readily than air. Such vibrations may be reduced by elastic support between the transformer base and

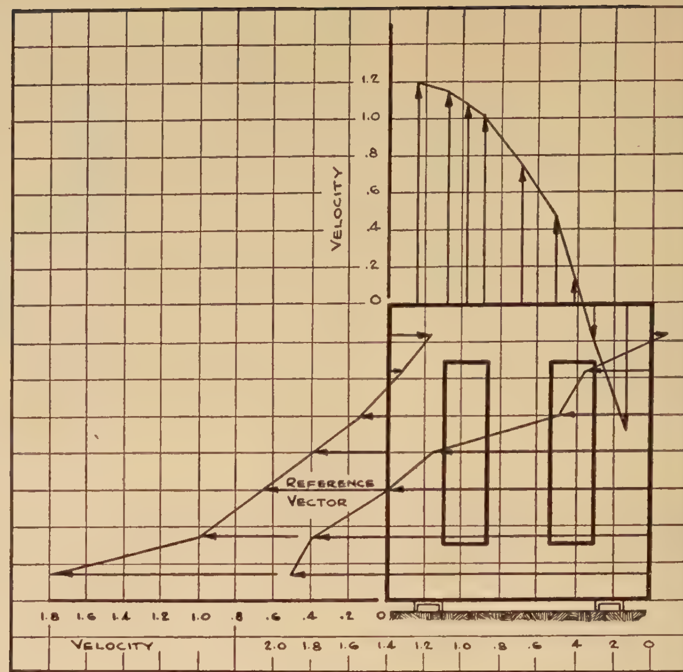
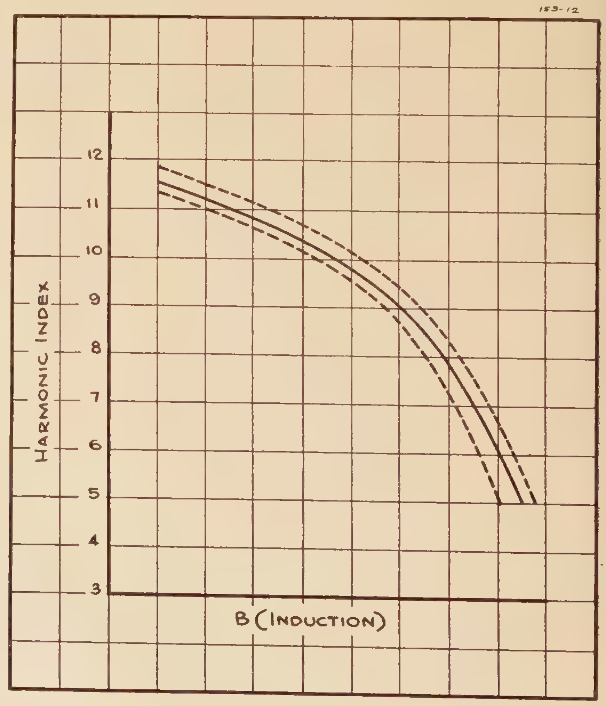


Figure 10. Core vibrations at 116-cycle vibrational frequency in a plane parallel with the laminations of a three-phase core

Figure 12 (right). Harmonic index of transformer steel corresponding to 40-decibel frequency response



Suppression of Magnetic Vibration and Noise of Two-Pole Turbine Generators

A. L. PENNIMAN, JR.
MEMBER AIEE

H. D. TAYLOR
MEMBER AIEE

THE constant striving for improvement in over-all economy in the generation of electric power by steam has resulted in the last three or four years in a rather rapid increase in the capacity of steam turbine generators built to operate at 3,600 rpm. One of the factors contributing to this growth was the progress made in the use of high-pressure and high-temperature steam which led to the application of a number of such turbines for superposition on existing comparatively low-pressure steam plants, as well as for straight through condensing operation. The operating experience with such recently developed 3,600-rpm generators ranging in capacity up to 66,667 kva has been unusually good. The troubles which have been experienced, either mechanical or electrical, have not been of a serious nature.

While 3,600-rpm generators have been built for many years, the double-frequency vibration and noise produced by them was not until recent years of much moment or concern. The comparatively recent machines with which we are here concerned are large as compared to the earlier ones and have in many cases produced an objectionable amount of 120-cycle noise and vibration, the noise being often an intense humming of all-pervading character, seeming to go all through the plant. The intensity of the noise, at some points, is materially affected by reflection from various smooth surfaces, being particularly loud where the reflected sound wave reinforces the original.

In addition, the actual amplitude of the mechanical vibration has been sometimes sufficient to result in severe vibration of many parts of the station structure or equipment such as beams, brackets, floor plates, housings or parts of them, even exciter brush arm brackets, latch mechanisms, or perhaps delicate relay parts. This is particularly so if the natural period of vibration of some beam or part is in resonance or near resonance with the vibration source.

Early investigations of the 120-cycle vibration and noise showed that they resulted when field excitation was applied to the generator and that in fact they were two aspects of the same disturbance. This definitely indicated that the cause was magnetic. The disturbance, as has been pointed out in a previous paper,[1] is due to the magnetic forces of a two-pole field rotor bringing about a distortion of the stator into an elliptical shape, the distortion revolving in synchronism with the rotor. Since each pole of the rotor pulls the stator radially inward, any point on the stator core vibrates at a frequency double that of rotation, or at a frequency of 120 cycles for a 3,600-rpm machine.

As is well known, the magnetic force of attraction between the stator and rotor at any given point varies as the square of the flux density at that point. Figure 1 has been plotted in terms of magnetic force or pull as determined from the flux distribution typical of a two-pole machine.

While the magnetic vibration has not been severe enough to have any apparent effect on the life of the stator winding or other parts, nevertheless, the noise has in many instances been so intense as to be very annoying to live with, which indicated that there was a need for some means of suppression or mitigation of this noise and vibration and led to the undertaking of a careful analysis of the problem. The presentation of the various phases of this analysis, together with a description of the development of an apparently complete cure for the double-frequency magnetic vibration nuisance by means of a simple form of resilient core mounting, is the subject of this paper.

Observations on Magnetic Vibration

Since the double-frequency vibration and noise are caused by distortion of the generator stator structure, the amount of this distortion is of primary importance. The frequency being high, special equipment is required for accurate measurement. Readings of vibration amplitude taken with an optical amplitude indicator on a representative large two-pole machine of early design are shown in figure 2. These were taken radially on the surface of the stator, and the plot shows the variation in amplitude along the length of the machine. The same curve applies to either side or the top of the generator, or at any angle in between, for *radial* amplitudes. With excitation removed, this vibration disappears, although there is usually a residual vibration at running speed frequency, transmitted from the rotor, which is small if the machine is well balanced. The residual vibration in this case is shown by the dotted curve.

The variation of this double-frequency

Paper 41-39, recommended by the AIEE committee on electrical machinery, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 15, 1940; made available for preprinting December 10, 1940.

A. L. PENNIMAN, JR. is general superintendent of electric operations, Consolidated Gas Electric Light and Power Company of Baltimore, Md. H. D. TAYLOR is in the turbine generator engineering department of the General Electric Company, Schenectady, N. Y.

1. For all numbered references, see list at end of paper.

---

the foundation. This elastic support should be correctly designed, otherwise its effect may be very detrimental. The elastic support should have a natural frequency considerably below the lowest impressed vibrational frequency produced by the transformer. Spring supports are, in general, not practicable. There are on the market special high-grade rubber compounds which do not lose their resilience appreciably with time.

The problem of transformer sound and methods for its reduction is far from being solved. With the exception of reduction in magnetostriction, no means have been found by which the sound level may be economically reduced. Continued research is being done on this problem. The company with which the writer is associated has a large soundproof room which is used to facilitate such investigations. This room has inside dimensions of 24 feet by 25 feet and 22 feet height. It is of a double-room construction. The outer room is of eight-inch brick walls with a seven-inch thick concrete roof. The inner room is completely insulated from the outer room. Its walls and ceiling are constructed of sound-absorbing material particularly effective for frequencies in the range from 100 to 1,000 cycles. A seven-inch air space separates the two rooms. The average attenuation is of the order of 55 decibels, which is sufficient for the work for which the room was designed.

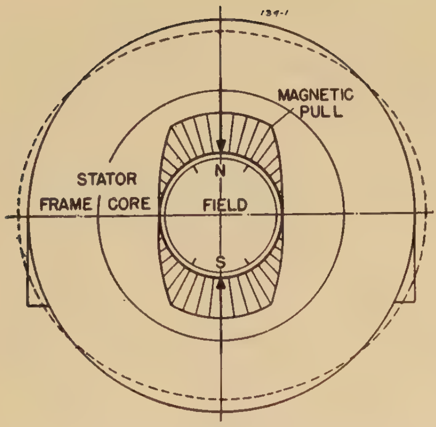


Figure 1. Magnetic pull of a typical two-pole a-c generator

amplitude with speed is shown in figure 3. It may be noted that, as speed is reduced below 3,600 rpm, with constant excitation, the amplitude drops off somewhat, but levels off to a definite value for zero speed. The shape of this curve is similar to part of a resonance curve, and suggests that if the speed could be carried considerably beyond 3,600 rpm, the amplitude would increase greatly, perhaps reaching a peak value at some higher speed.

Analytical Approach to Problem

Consideration of data such as are shown in these figures suggested an analytical approach to the problem to account for the observed vibration, along the following lines:

(1). Evaluation of the magnetic forces acting radially in the air gap between rotor and stator;

(2). Calculation of the deformation of the stator structure by these forces, considered as acting statically, that is, with the rotor at rest;

(3). Estimation of a resonance "build-up" factor (ratio of running amplitude to static deformation) based upon the relationship of the frequency of the magnetic forces at running speed to the natural frequency of the stator vibrating as a cylindrical ring with a four-node pattern.

Tests on Stiffness of Stator Elements

The magnetic forces were found to be rather large, equivalent roughly to two concentrated opposite radial loads on the stator of the order of 50,000 to 100,000 pounds each in large machines. The static deformation of the stator frame by such forces, assuming at first that the core laminations had no stiffness of their own, was calculated by well-known ring formulas[2,3] to be far greater than the observed vibration. It seemed therefore that the laminations must contribute a large share of the total stiffness of the stator. As a check on this point, deflection tests were made on a full-sized stator frame of greater than average stiffness before and after the laminations were assembled, with results as shown in figure 4. The frame was set on the factory floor and loaded with heavy rotor forgings laid on top of it on wooden chocks, and the deflection measured by means of dial indicators set to register the change in the vertical diameter. Upon removal of the loads, the indicators all returned to zero. It will be noted that with the heaviest load, the bare frame deflected 10.5 mils, as compared with 1.3 mils after assembly of the core.

In anticipation of these results, and to settle the question as to whether this great stiffness was a property of the tightly pressed core itself or depended upon assembly of the core in the frame,

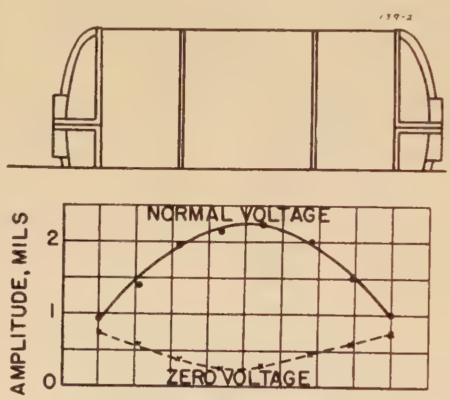


Figure 2. Distribution of vibration on stator of a two-pole generator

a ring had been made of some of these same laminations pressed together with rectangular steel bars as shown in figure 5. This ring was also subjected to deflection tests, by loading it across a diameter with a hydraulic jack, and measuring the deformation with dial indicators in much the same way as on the frame. It was found that this ring of punchings was quite elastic; that it would take loads up to several times the normal magnetic load, and return to its original shape; and that it was exceedingly stiff, sufficiently so to account fully for the difference in stiffness between the bare frame and the stacked frame. Also, while the ring stiffness varied somewhat with the tightness of clamping, this effect was comparatively slight so long as the laminations were reasonably tight. In short, the core was found to be a cylinder of great strength and stiffness independent of the generator frame.

Tests to Determine Natural Frequency of Core

Other rings of punchings were tested with similar results. Further tests were made on them to determine the natural frequency as a cylindrical ring vibrating radially with a four-node pattern. The two types of tests, for static stiffness and for natural frequency, were correlated, and it was found possible to calculate the natural frequency of a core structure with reasonable accuracy. In all cases, it was found to be high, of the order of 160 to 200 cycles in the largest machines, and higher in smaller machines.

Use of Resonance Curve in Calculating Magnetic Vibration

This information made it possible to carry through with the three steps suggested for the calculation of the amplitude of magnetic vibration of two-pole generators in general. The stiffness of the frame usually being small in comparison with that of the core, little error results from leaving the frame entirely out of the calculations. The first two steps, to determine the magnetic forces and the resulting static deflections of the cylindrical ring of punchings, are carried out by well-known methods that do not need to be repeated here. The third step makes use of a resonance curve such as that shown in figure 6. Here amplitude is plotted against the frequency of the deflecting force. For zero frequency, i.e., a steadily applied force, the amplitude is shown as 1.0, which represents the static deflection. With increasing frequency, the amplitude increases and reaches a peak value at resonance, when the frequency of the deflecting force equals the natural frequency

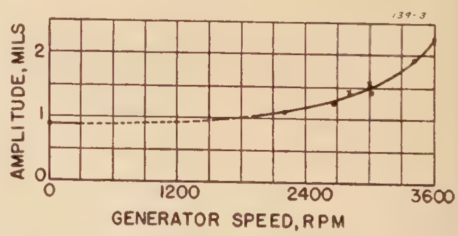


Figure 3. Variation of magnetic vibration with speed

of the setup. The frequency scale is also on a per-unit basis, with 1.0 representing resonance. For higher frequencies beyond resonance, the amplitude decreases rapidly. This relationship between amplitude and frequency is rigorous[4,5] for any simple system in which the disturbing force remains constant in magnitude

as the frequency varies. It has been assumed to apply to a cylindrical ring. Damping has been neglected; if taken into account it would reduce materially the amplitudes near resonance, as shown by a sample dotted curve. However, the four-node natural frequencies of the generator cores were found to be so far above the impressed frequency of 120 cycles that damping can be neglected. The use of the curve is fairly obvious. It merely shows a "build-up" factor, representing the increase of the running amplitude above the static deflection. For example, if the natural frequency of the stator core is determined as 200 cycles the ratio of impressed frequency to natural frequency is 120/200 or 0.6; and the "build-up" factor is 1.56.

Improvement Obtained by Increased Radial Depth of Core

Calculations were made along these lines for all large 3,600 rpm generators made by the General Electric Company. Agreement between the calculations and the maximum of test observations similar to those plotted in figure 2 was very satisfactory. It was obvious from the results that considerable reduction in the vibration could be obtained by the use of punchings of increased radial depth. The greater stiffness of such "deep core" machines helps in two ways: (1) it reduces the "static" deformation; and (2) it increases the natural frequency so that the "build-up" factor is also reduced. Deep-core construction has been used in quite a number of generators in the past two years, with a gratifying reduction in the double-frequency disturbance. The ratio of improvement in the largest machines has been of the order of two to one.

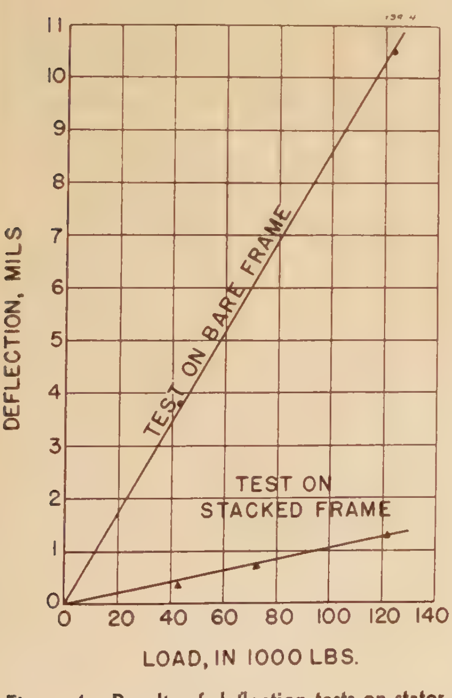


Figure 4. Results of deflection tests on stator frame

Consideration of Resilient Mounting of Core to Isolate Vibration

Although the improvement obtained by the simple expedient of deepening the core was considered to be sufficient to remove most of the nuisance effect of the noise and vibration in all cases where station acoustics are reasonably good and mechanical resonance is avoided in adjacent structures, nevertheless it seemed the severe torsional effect of short circuits. A complete treatment of these matters is entirely beyond the scope of this paper. They will be briefly discussed, however, in the next few paragraphs.

Tangential Displacements of Cylindrical Rings

A tangentially rigid but radially flexible type of mounting was suggested independently by several engineers within the General Electric Company, and was given serious consideration. Its effectiveness would apparently depend upon the amount of tangential vibration accompanying the radial vibration at the point

Figure 5. Setup for deflection tests on ring of core laminations

desirable to see what could be done to eliminate the magnetic disturbance almost entirely. A suggestion to this end had been made by L. P. Grobel, shortly after the first large 3,600-rpm generators came to test. His proposal was to isolate the vibration by mounting the core on spring members within the stator frame. This seemed like a rather radical departure, but the tests described in preceding paragraphs demonstrated that the tightly pressed laminated cores had great strength and stiffness of their own, and indicated that the isolation idea was an inviting possibility. A number of complications, however, had to be faced. First, should the spring members provide radial flexibility only, and be rigid tangentially; or should they be flexible both ways? Second, if the frame is not attached rigidly to the core, its own four-node natural frequency will determine its response to the stimulation coming through the spring members, and must be taken into account. Third, the core should apparently be mounted in such a way that it will not have natural frequencies for bodily motions which would cause it to respond unduly to the running speed frequency disturbances caused by unbalance of the rotor. Fourth, the core mounting must be designed to withstand

of attachment, at the outside diameter of the core, or farther out if a double frame should be used. It is not at once obvious that there should be any tangential motion at all, although it was pointed out long ago by Lord Rayleigh[6] that in the case of a *thin* circular ring, elliptical distortion or four-node vibration resulted in a tangential displacement of the nodal points equal to just 50 per cent of the maximum radial displacement. This is illustrated in figure 7, from which the reason for the tangential displacement may be seen. The distance around a quadrant of the deflected ring, from one 45-degree point to the next, is obviously greater across the major axis than across the minor axis, so that, unless the ring is forcibly stretched in two quadrants and shortened in the other two, the "nodal" points at 45 degrees must move tangentially.

Two-pole generator cores, however, are not thin rings, but relatively deep ones. An investigation was made to determine how the tangential displacement might vary with the ring depth. The curves in figure 8 are drawn to illustrate some of the results of an analysis made by Doctor H. Poritsky and H. D. Snively. These show that deep rings have a tangential displacement of more

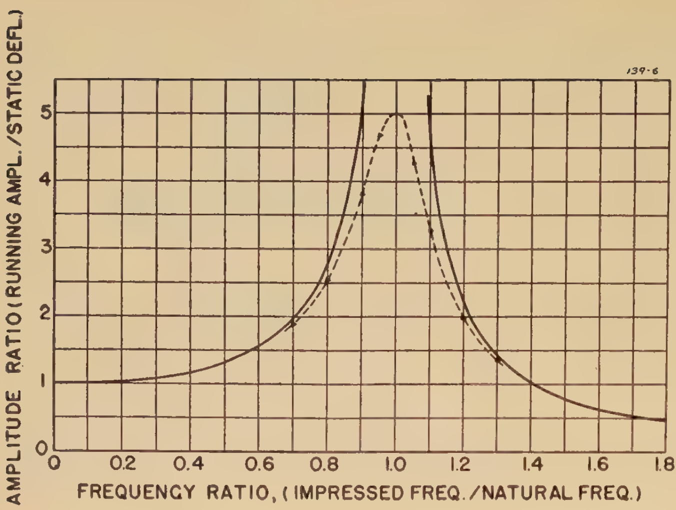


Figure 6. Basic resonance curve

than 50 per cent of the radial displacement, at the inside diameter; but less than 50 per cent at the outside. The exact values depend upon the depth ratio (outside diameter)/(inside diameter). Amplitude observations during the tests for the natural frequency of rings of punchings, described in a previous paragraph, gave an excellent check on these curves, as shown by the X points (figure 8). It seems that for two-pole generator cores of normal proportions, with a ratio of outside to inside diameter (over the slots) of 1.5 to 1.6, the tangential vibration on the outside diameter is likely to be about 20 per cent or more of the radial vibration. Now, the frame may also be considered as a deep ring, with a ratio of outside to inside diameter of the same order of magnitude as the core. Consequently, the tangential vibration at the *inside* diameter of the frame is likely to be about 80 per cent of its radial vibration. Thus, if the point of attachment for a tangentially rigid core mounting is at the outside diameter of the core, something like 20 per cent of the radial vibration of the core would be tied in rigidly with 80 per cent of the radial vibration of the frame. The result would be a reduction of about four to one in the radial vibration at the surface of the frame. Such an improvement would be quite worth while, but it was felt that a higher ratio of reduction would be desirable.

Importance of Natural Frequency of Stator Frame

Consideration of a resilient mounting having both radial and tangential flexibility indicated that an improvement ratio of 10 or 20 to 1, or even higher, could be obtained by suitable design of the spring members and the frame. In brief, the spring members must be relatively flexible, and the frame relatively stiff. The static performance of such a combination is readily calculated. The vibrational loading of the frame is computed as the product of the amplitude of the core and the gradient of the spring members. This neglects the yielding of the frame, which is intended to be negligibly small anyway. Both tangential and radial loading must be taken into account. However, the running performance depends upon the natural frequency of the frame, in the same manner as the running amplitude of the core depends upon its natural frequency. Strictly, the core, spring members, and frame form a compound elastic system with two natural frequencies, both of which are different from the natural frequencies of the core and frame considered separately. The behavior of such a system has been carefully worked out by methods described in chapter V of reference 4. With the aid of some simplifying assumptions, however, calculation of the running performance to a close degree of approximation can be made, using the ordinary basic resonance curve of figure 6. The effect of the frame and spring members on the stiffness, natural frequency, and running amplitude of the core is neglected; but a correction to the natural frequency of the frame due to the spring members may be required, especially if the frame frequency is low, below 120 cycles. The static deformation of the frame, which would be produced by the combined radial and tangential loading due to the *running* amplitude of the core acting on the spring members is calculated, and multiplied by the "build-up" factor based upon the natural frequency of the frame.

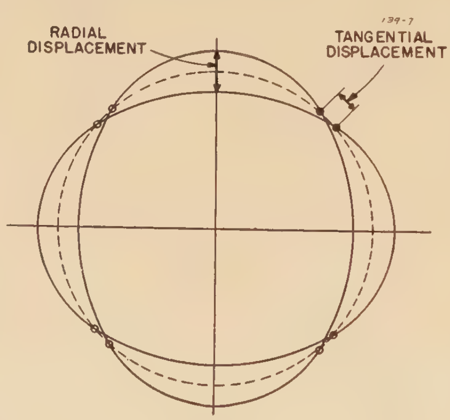


Figure 7. Sketch illustrating tangential displacements for a thin ring

For this purpose, it is of course necessary to know the four-node natural frequency of the frame. To date, it has been necessary to use test information on this point. Test equipment available for vibrating turbine wheels and buckets has been used with the addition of some small but powerful a-c magnets, which are set to pull diametrically across the bore of the frame under test. Even the largest and heaviest frames are set into vibration in this way, and by varying the frequency of the a-c supply to the magnets, the resonant frequency of the frame is readily determined. In general, it is felt that a high natural frequency (above 120 cycles per second) is desirable for frames to be used with resiliently-mounted cores, for the reason that it avoids a "critical speed" or resonance peak of frame vibration which would otherwise occur below running speed, if the generator is brought up or down with excitation. It is undoubtedly practical, however, to use resilient mountings with frames having natural frequencies below 120 cycles, if the frame can be well damped to limit the momentary vibration encountered in passing through resonance, or if the excitation is reduced sufficiently or removed at that speed.

Mechanical Effects of Rotor Unbalance and Short-Circuit Torque

So far, the discussion has centered about the functioning of the resilient core mounting to isolate the magnetic vibration. Now, attention is directed to possible difficulties from other sources.

The core, end flanges, and winding structure, taken together, comprise by far the heaviest part of a two-pole generator. If "floated" on spring members, there is the possibility that mechanical resonance might take place for bodily motion of this heavy mass in response to stimulation coming from rotor unbalance. Considered as a simple mechanical system with the frame support on the

foundation assumed to be rigid, the obvious solution is to make the natural frequencies of the core on the spring members low for both translation, i.e., "straight bouncing," and for rotation about an axis at right angles to the shaft, which can be called "rocking." Actually, the foundation is never rigid; for large machines it is far from being so, especially in the horizontal plane. The result is a complicated elastic system, comprising the rotor, the frame, and the spring-mounted core (not to mention the turbine), all mounted on a foundation of considerable mass and with flexibility both for horizontal and vertical motion. Such systems have been investigated by E. H. Hull, using a novel experimental technique described in a recent paper.[7] He finds a whole series of resonance speeds, depending upon the critical speeds of the rotor (as calculated for rigid bearing supports) and the natural frequencies of the spring-mounted core, as well as the mass and flexibility of the foundation. Fortunately, it seems to be possible to control these resonance speeds, for ordinary values of shaft criticals and foundation characteristics, by making the natural frequencies of the spring-mounted core rather low, say, of the order of 1,200–1,500 vibrations per minute. Also, none of them involve much vibration if the machine is properly balanced.

Special consideration must also be given to the severe transient short-circuit torques characteristic of turbine generators, in order that the spring members shall not be overstressed. Instantaneous peak values of the applied torque, although they may be many times normal rated torque, are ordinarily not high enough to cause concern in this respect. Their magnitude is usually of such an order as would about take the gravity load off one foot of the generator and double it on the other. Since the considerable inertia of the core is interposed between the short-circuit torque, applied at the air gap, and the spring members outside the core, the stresses in the spring members are not a direct function of the applied torque alone but depend upon the torsional displacement of the core relative to the frame. This displacement can be calculated by methods[8,9] previously developed for analysis of short-circuit torques at the couplings of turbine-generator sets.

These methods are rather well known, but a few remarks about them might be in order here. The simplest approach considers the torques as suddenly applied, but neglects the decrements, and assumes a rigid foundation such that the torsional system has only one natural frequency. On this basis, the maximum displacement may be computed as the sum of a series of components of displacement which occur at the applied torque frequencies (principally 60 and 120 cycles) and also at the torsional natural frequency of the system. Each of these components is a function of the frequency ratio (impressed frequency/natural frequency), in a manner very similar to the basic resonance curve of figure 6. However, it appears advantageous in this case to keep the torsional natural frequency well below the lowest frequency of the impressed torque. When foundation flexibility is taken into account, the system becomes a compound one with two natural frequencies. The analysis becomes considerably more elaborate but has been worked out fully on the basis of neglecting the mechanical damping and the torque decrements. These assumptions, of course, are on the safe side, but before this study of short-circuit torques can be considered complete, these factors must be taken into account. In general, however, it is found that foundation flexibility reduces the maximum displacement of the core relative to the frame below that which would occur on a rigid foundation.

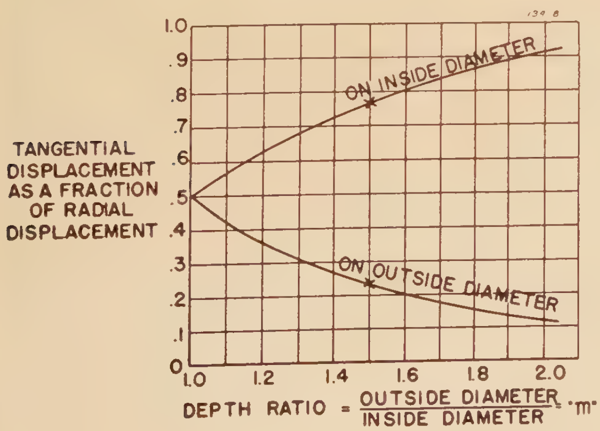


Figure 8. Tangential displacements in deep rings

Description of Resilient Core Mounting as Built

A resilient core mounting and a nonresonant stator frame were designed along these lines for a 31,250-kva air-cooled generator. A photograph of the frame is included as figure 9, and figure 10 gives a close-up view of the assembled spring members. These are twin sets of spring bars of rectangular section, attached by bolting and welding to the bore of the frame and arranged in three groups lengthwise. The long dovetail key bars on which the core is stacked, are attached by body-bound studs to the centers of the spring bars, which provide a sturdy tie between the core and the frame, rigid lengthwise but with some

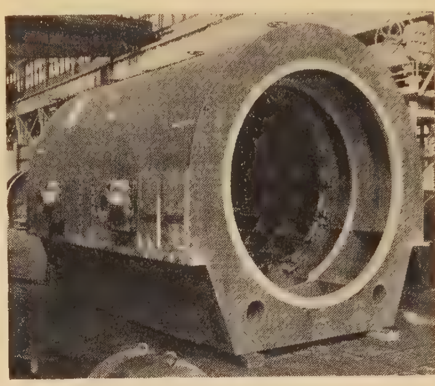


Figure 9. Frame of 31,250-kva generator with resilient core mounting

flexibility both in the radial and tangential directions. The spring bars are really beams with fixed ends, and with heavy bosses at their centers where they are bolted to the dovetail key bars and also at their ends where they are attached to the frame, so that there are no moving joints to wear out. Fatigue seems to be completely out of range for these bars, as the alternating component of stress is of the order of two per cent of the elastic limit of the material, superposed upon steady gravity stresses of about 20 to 25 per cent. And fatigue needs to be out of range, as at 120 cycles per second these bars must undergo more than 10,000,000 cycles of duty per day. The frame was also specially designed, to have a high four-node natural frequency, well above 120 cycles. The test value on the bare frame, without end shields, was 201 cycles. On this basis, the expected performance of the resilient core mounting was a reduction of the magnetic vibration from core to frame of about 30 to 1. When this machine came to test at the factory, it met our expectations fully. In fact, no 120-cycle vibration could be detected at the middle of the frame, by touch or by

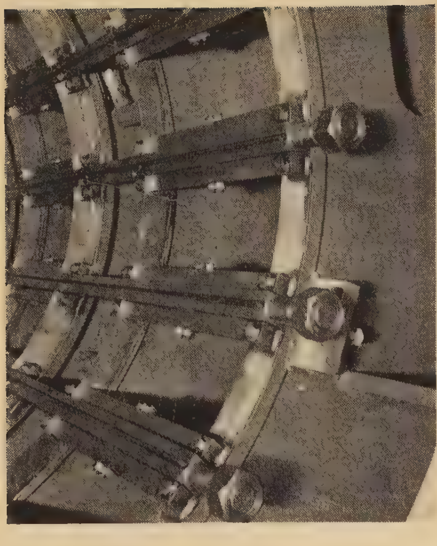


Figure 10. Close-up view to show spring bars in 31,250-kva generator

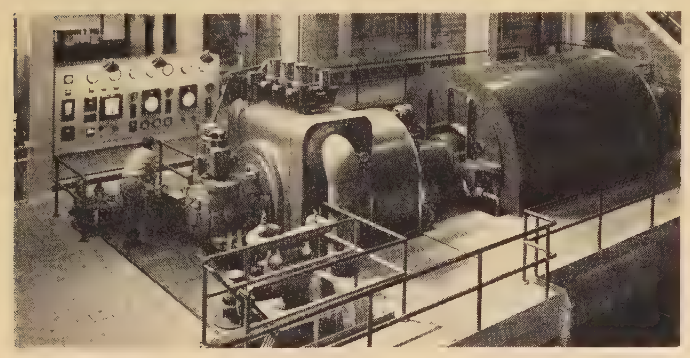


Figure 11. Turbine unit with 31,250-kva generator having resilient core mounting, Westport plant, Consolidated Gas Electric Light and Power Company of Baltimore, Md.

means of optical vibration indicators, Frahm vibrating reed tachometers, or a vibration-velocity pickup device connected to a cathode-ray oscillograph. The core was reached by means of rods inserted through small holes drilled in the frame, and showed about 1.3 mils of magnetic vibration. But it was impossible for a man standing alongside the generator to tell, by touch or by hearing, when excitation was applied or removed.

Operating Results

This 31,250-kva air-cooled generator, as built with resilient core mounting and nonresonant stator frame, was installed at the Westport plant of the Consolidated Gas Electric Light and Power Company of Baltimore, Maryland, and went into service on August 10, 1940. Figure 11 shows this generator and driving turbine as installed at Baltimore.

The turbine driving this generator was built for operation at a throttle pressure of 1,250-pounds gauge 900 degrees Fahrenheit, being supplied with steam from two high-pressure boilers. The turbine exhausts into the 200-pound steam mains of the earlier Westport plant but with piping arranged for specific superposing if desired on two 25,000-kva 200-pound regenerative condensing units, which were the last 200-pound units installed at Westport.

The operation of this superposed 3,600-rpm unit has well demonstrated the value of the new core mounting for suppression of 120-cycle core noise and vibration, the operating results being quite in agreement with the factory tests. In actual service, a man standing alongside of the machine could not detect by touch or hearing the application or removal of field excitation.

Other machines incorporating the improved type of core mounting are now being built, and it is expected that this feature will be applied to many 3,600-rpm generators of the future.

References

1. Special Problems of Two-Pole Turbine Generators, **C. M. Laffoon** and **B. A. Rose.** AIEE Transactions, volume 59, 1940 (January section), pages 30–3.

2. The Design of Large Electrical Machine Frames, **Ralph Poole.** *Journal* of the Institute of Electrical Engineers (England), volume 77, 1935, pages 176–88.

3. Strength of Materials (book), **S. Timoshenko.** D. Van Nostrand Company, part II (2nd volume), 1930, pages 434–8.

4. Vibration Prevention in Engineering (book), **A. L. Kimball.** John Wiley and Sons, 1932, page 30.

5. Vibration Problems in Engineering (book), **S. Timoshenko.** D. Van Nostrand Company, 2nd edition, 1937, pages 14–16.

6. Theory of Sound (book), **Lord Rayleigh.** MacMillan and Company, 2nd edition, volume 1, 1894, page 388.

7. The Effect of Foundation Stiffness on the Resonant Frequencies of Rotating Machines, **E. H. Hull.** *Journal of Applied Mechanics*, volume 8, 1941.

8. Single Phase Short Circuit Torque of a Synchronous Machine, **Nickle, Pierce,** and **Henderson.** AIEE Transactions, volume 51, 1932, pages 967–73.

9. Transient Torques in Synchronous Machines, **M. Stone** and **L. A. Kilgore.** AIEE Transactions, volume 52, 1933, pages 945–53.

High-Potential Testing Equipment for Quantity Production

C. M. SUMMERS
MEMBER AIEE

Introduction

MANUFACTURERS of electrical apparatus and appliances are aware of the value of high-potential insulation tests and have endeavored constantly to improve testing facilities and methods. Practical circumstances very early gave rise to the practice of applying a short-time test voltage substantially above the normal excitation of the apparatus or appliance. Because of the availability and simplicity of amplitude control, alternating voltage of ordinary power frequency has been used and the test voltage levels have been developed through operational experience. Occasionally circumstances have made the use of power frequency impractical; hence higher frequencies and direct voltage have been resorted to. Also, surge voltage tests have been used increasingly in an effort to simulate transient voltages which occur in field circuits.

For large apparatus and for high-voltage equipment the dielectric testing sets have been standardized and the testing procedure has been generally established. In this field a generous amount of time can be allowed for conducting tests, because the quantity of apparatus manufactured is comparatively low.

Because of the large quantity of small apparatus and low-voltage equipment now manufactured, high-potential testing must be co-ordinated with production circumstances where rates of 20 or 30 complete dielectric tests per minute are commonly encountered. Accordingly, the recognized practice of gradually raising and lowering the test voltage is entirely impractical from the standpoint of time consumed. Consequently many of the factors which have been so carefully considered in the high-voltage field have been neglected in low-voltage testing.

The purpose of this paper is to point out that the simplicity of low-voltage testing does not obviate surge voltages and that the same general fundamental factors established for high-voltage testing also apply to low-voltage testing. In this paper an attempt has been made to evaluate the surge voltages in terms of their effect on the breakdown of insulation. First, a cathode-ray oscillograph study was made to determine the magnitude of the surges. Then a number of comparison tests were made on a selected insulation to determine the comparative breakdown strength with and without influence of the surges.

As a result of these investigations it was found that the magnitude of the surge voltage varied considerably depending on the method used for limiting the short-circuit current and on the characteristics of the dielectric. In some instances, surges of 100 per cent above the normal test voltage were measured. In a controlled test, the surges reduced the apparent breakdown voltage of a specific insulation by roughly 25 per cent. It has been found that a properly co-ordinated high-potential transformer and a resistance potentiometer control forms a suitable system for testing low-voltage apparatus. The system is relatively free from surge voltages and it does not interfere with high-speed testing. This method also has led indirectly to the development of a cathode-ray fault detector which has been very useful in analyzing the physical characteristics of the dielectric and the type of failures that occur.

Present Practice

The testing equipment for this low-voltage apparatus can be obtained and installed with comparative ease in any production line. The test voltage can be conveniently controlled and easily applied. Usually, some means of limiting the short-circuit current is employed in order to minimize the material damage to the apparatus or appliance in case the dielectric fails. A pair of insulated electrodes, called stickers, permanently connected to the high-voltage terminals of the high-potential transformer, is commonly used to apply the test voltage between the windings and the frame or ground of the apparatus under test. In some cases, however, two or more units may be connected in parallel to the high-potential testing transformer which is then energized for a brief period of time. In either case, surge voltages are liable to occur in the high-voltage circuit which casts some doubt on the effective value of the test voltage.

Switching Surges

It is common knowledge that the interruption of the excitation circuit of a transformer will produce a transient voltage across its terminals. The amplitude of the impulse is proportional to the rate of change of flux in the magnetic circuit, and it is dependent on the position on the

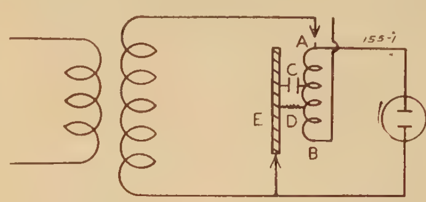


Figure 1. Equivalent high-potential testing circuit

A—Arc
B—Winding of apparatus
C—Capacitance of winding to ground
D—Resistance of insulation
E—Frame of apparatus (ground)

Figure 2. Oscillogram of voltage across dielectric during high-voltage switching

Transformer controlled by variable-voltage autotransformer

Normal crest voltage—3,530 volts

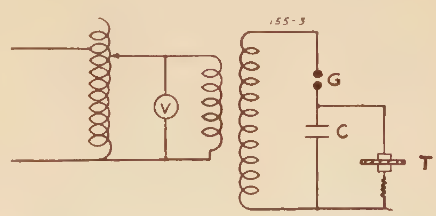


Figure 3. Test circuit for evaluating effect of switching surges on dielectric strength of paper

G—Sphere gap
C—Capacitor equivalent to the capacitance of low-voltage apparatus
T—Test sample

Paper 41-55, recommended by the AIEE committee on instruments and measurements, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted October 17, 1940; made available for preprinting December 12, 1940.

C. M. Summers is electrical engineer at the works laboratory of the General Electric Company, Fort Wayne, Ind.

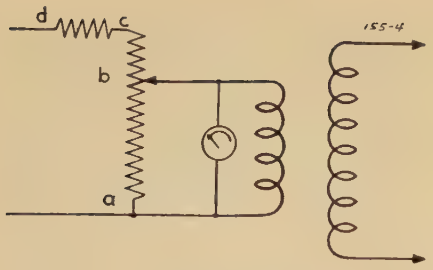


Figure 4. Potentiometer-controlled testing transformer

Minimum series resistance—*d-c*
Maximum parallel resistance—*ca*

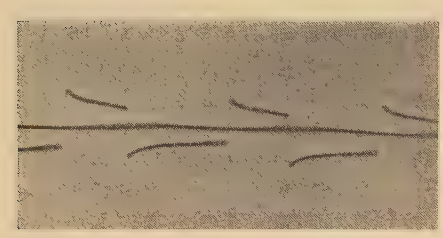


Figure 5. Oscillogram of voltage across dielectric during high-voltage switching

Transformer controlled by potentiometer normal crest voltage 3,530 volts

flux-time curve at which the circuit is opened. Whenever high-potential testing methods employ low-voltage switching, it is obvious that the dielectric circuit will be subjected to an indefinite abnormal voltage. Furthermore, the maximum amplitude of the surge may occur when the transformer is de-energized at the conclusion of the test. The dielectric may fail at this final instant and if it does, it may not be detected unless a subsequent test is made.

High-voltage switching is employed every time the stickers are applied and removed from the apparatus. An arc occurs when the stickers are applied and another when they are removed. The testing circuit, consisting of resistance, inductance, and capacitance, may have excessive transient voltages induced in or applied to all parts of the circuit during this arcing period.

A cathode-ray oscillograph connected as shown in figure 1 will indicate the actual voltage to which the dielectric is subjected. When the contact at *A* is solidly closed the normal transformer voltage is applied to the dielectric. However, when an arc is established at *A* a series of transients or impulses are impressed on the test piece at the beginning of each one-half cycle. The oscillogram in figure 2 shows this condition for a common type of testing circuit. This shows a crest voltage of over 5,000 volts whereas the steady-state test voltage had a crest value of 3,500 volts. This is somewhat equivalent to superposing an impulse on the power frequency. It has been observed in the past that under these conditions a flashover of an insulation may not be followed by a power arc, particularly when the total voltage amplitude is near the flashover value for that insulation. Under the somewhat similar conditions as illustrated by figure 2, the insulation may be partially damaged, by a pinhole puncture, for example, which has not been followed up by a power arc. This may be a sufficient cause for a future failure at a lower test voltage. This experience indicates that it is desirable to maintain a sinusoidal voltage on the test piece throughout the entire test period.

Field Data

In order to obtain some field data on the effect of arcing surges some special tests on fractional-horsepower motor armatures were conducted with a pair of stickers connected in parallel with the regular production line. The armatures were tested at 1,500 volts, but would normally withstand 2,500 volts. The test pair of stickers was connected to an armature and an arc maintained between one sticker and the winding for a period of

Table I. Effect of Surges on Dielectric Strength of Paper

Sample Number	Breakdown Voltage—No Arcing (Voltmeter Readings)	Breakdown Voltage Arcing to Simulate Removal of Stickers (Voltmeter Readings)
1	1,330	1,170
2	1,670	1,330
3	1,700	1,280
4	1,860	1,375
5	1,430	1,265
6	1,460	1,170
7	1,400	1,230
8	1,670	1,330
9	1,530	1,350
10	1,400	1,200
11	1,370	1,140
12	1,310	1,150
13	1,370	1,170
14	1,400	1,220
15	1,670	1,330
16	1,700	1,310

time. Five consecutive armatures were broken down on the production line during this test, although a voltmeter still indicated an rms test voltage of 1,500 volts.

In another instance, a plate-glass condenser was used as a dielectric load and during the arcing period a sufficiently high-surge voltage was established to flash over the one-fourth-inch plate glass of the condenser, although the test voltage as indicated on an instrument remained at 2,500 volts. The condenser had a sinusoidal flashover value of 6,000 volts.

A test circuit shown in figure 3 was established to measure the effective breakdown value of the surges initiated by an arc in the high-voltage circuit. The sphere gap *G* represents the stickers and it was used merely to control the arc and not to measure voltage. Past experience has indicated that the capacitance of the dielectric of low-voltage apparatus and appliances varies from 0.0005 to 0.002 microfarad. A 0.001-microfarad capacitor, chosen as a representative load, was connected in series with the gap so that the voltage across it is comparable to that across the dielectric of the apparatus in actual practice. A transformer having about three per cent reactance was used for the source of high potential. Several selected samples of an insulation, consisting of four layers of 0.0005 condenser paper, were used as test specimens and

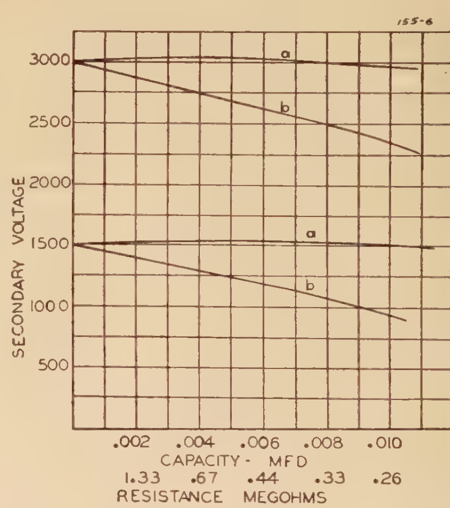


Figure 6. Voltage-regulation curve of 0.25-kva 3,000-volt potentiometer-controlled transformer

a—Capacitance load
b—Resistance load

connected directly across the capacitor. Each specimen was large enough to obtain two breakdown tests, one when a sinusoidal voltage was applied and the other when surges were produced by the arc. The first test was obtained by closing the sphere gap *G* and raising the primary voltage very slowly by means of a variable-voltage autotransformer until breakdown occurred. The second test was obtained by setting the primary voltage at some low value and opening the gap *G* until the arc was extinguished. (This action simulates the removal of stickers from the apparatus.) The sup-

ply voltage was raised in small increments and the procedure repeated until the specimen broke down and in each case the rms voltmeter readings were recorded. The results, shown in table I, indicate that the breakdown voltage is 20 per cent lower when the surges are present or in other words the dielectric is subjected to a higher level than the voltmeter indicates.

Surge voltages varying from 25 per cent to 100 per cent above the test voltage are commonly found in testing installations employing stickers, and utilizing reactance to limit the short-circuit current. Even when reactance is not deliberately introduced to limit the current, and when a testing transformer of normal design with less than five per cent reactance is used, the surges are still present. They may not be severe for many types of apparatus where the factor of safety is large. Furthermore, the degree of damage the surge can create in the insulation has not been conclusively established. The serious factor involved, however, is the uncertainty of the actual voltage to which the dielectric is subjected.

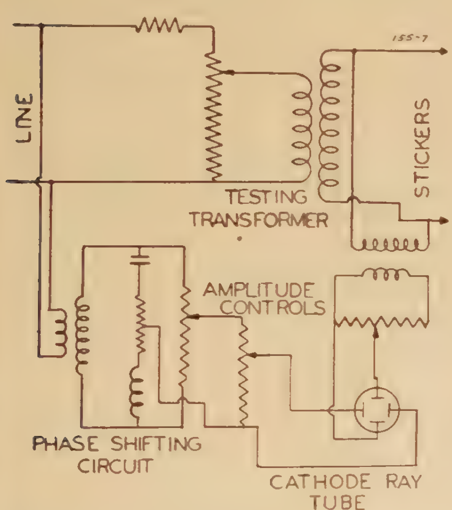


Figure 7. Circuit diagram for potentiometer-controlled testing transformer and cathode-ray fault detector

Methods of Reducing Surge Voltages

Resistance inserted in the high-voltage circuit in series with the test load will greatly reduce the surges appearing across the dielectric. In one case it was found that 50,000 ohms in the secondary of a 0.25-kva low-reactance transformer reduced the surges to a negligible amount. An equivalent resistance on the low-voltage side of the transformer similarly reduced the surges. A circuit shown in figure 4 has been found to be relatively free from all types of surges caused by low- or high-voltage switching, because the parallel resistance tends to absorb the energy of the low-voltage switching.

The effectiveness of the potentiometer control was demonstrated in the following manner. A transformer with a rating of 0.25 kva with three per cent reactance and a secondary voltage of 2,500 volts with 110 volts on the primary was supplied from a variable-voltage autotransformer. Surge voltages initiated by low-voltage and high-voltage switching were measured across a 0.003-microfarad capacitor load. The value of the surge most often obtained is given in table II as a percentage of the open-circuit secondary peak voltage.

Table II. Surge Voltages in a Circuit Controlled by a Variable-Voltage Autotransformer

Normal Secondary Voltage	Surges in Per Cent of Normal Secondary Peak Voltage: Primary Switching	Surges in Per Cent of Normal Secondary Peak Voltage: Secondary Switching
2,500	200	250
1,500	200	200
900	200	200

The variable-voltage autotransformer then was replaced by a potentiometer, or a resistance control as in figure 4 and the switching repeated. The results are shown in table III. A typical oscillogram of the high-voltage switching surge is shown in figure 5, and compares with figure 2 for the previous case. Satisfactory operation is thus assured with the potentiometer control if the series portion is limited to some predetermined minimum value of resistance and also if the parallel portion is limited to some maximum value.

Any type of testing circuit will supply a limited load when some means of current limitation is employed. Figure 6 shows the voltage-load curves for a potentiometer-controlled circuit. The capacitance of the dielectric circuit does not have a great effect on the regulation, curve *a*, especially in the range encountered in low-voltage apparatus. The resistance of the dielectric, however, does cause an appreciable regulation, curve *b*. Therefore, if it is desired to maintain a regulation of less than three per cent the resistance of the dielectric should not be lower than three megohms.

The high-voltage wave form can be maintained reasonably sinusoidal. If the series resistor alone is used, the normal exciting current required by the transformer causes an appreciable voltage distortion. If, however, the current through the resistor *ab* in figure 4 is approximately three times the value of exciting current, the wave form is acceptable, with a harmonic content of less than five per cent. The amount of distortion, of course, depends materially on the degree of saturation in the transformer core, but if this is maintained at a reasonable value, a good high-voltage wave form can be maintained.

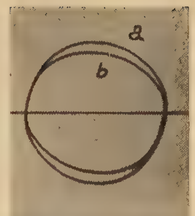


Figure 8. Lissajous figure of test voltage

a—Open circuit
b—Resistance load

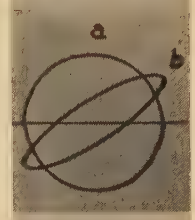


Figure 9. Lissajous figure of test voltage

a—Open circuit
b—Capacitance load

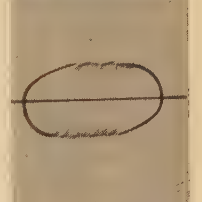


Figure 10. Lissajous figure of test voltage with corona in insulation

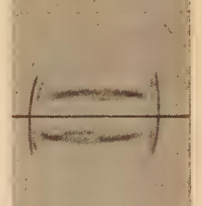


Figure 11. Lissajous figure of test voltage when arc is jumping through insulation

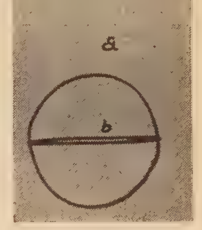


Figure 12. Lissajous figure of test voltage

a—Open circuit
b—Short circuit

Fault Detection

The arrangement of resistors just discussed permits an easy detection of short

Table III. Surge Voltages in a Circuit Controlled by a Potentiometer

Normal Secondary Voltage	Series Resistance (Ohms)	Parallel Resistance (Ohms)	Surges in Per Cent of Normal Secondary Voltage: Primary Switching	Surges in Per Cent of Normal Secondary Voltage: Secondary Switching
2,500	73	250	104	100
1,500	420	250	103	100

circuits because the voltage on both sides of the transformer drops in accordance with the severity of the failure in the dielectric. If the organic dielectric materials are moist, due to high humidity, the conduction current will be high, and the transformer regulation will cause the voltage to drop. Usually a high-leakage current will not destroy the insulation, but it will cause a definite indication of some abnormal condition.

A cathode-ray oscilloscope has proved to be a very useful tool in connection with the testing circuit shown in figure 4 for analyzing the type of faults that may occur in dielectrics.

Cathode-Ray Oscilloscope Fault Detector

Figure 7 shows the circuit diagram of the dielectric testing transformer, potentiometer, and cathode-ray circuit. The adjustable phase-shifting circuit permits the voltage on the horizontal plates to be shifted 90 degrees from the test voltage. The amplitude of voltage on both the horizontal and vertical plates can be adjusted so that the image on the cathode-ray tube screen can be made to appear as a circle as shown in figure 8*a* for the normal test voltage. When voltage is applied to a test sample through the stickers, the image will remain unchanged if the dielectric is perfect. If the insulation contains excessive moisture there will be a high value of conduction current, hence the voltage on the vertical plates will drop and the image on the cathode-ray tube will change to an ellipse as in figure 8*b*.

A high-capacitance current flowing through the dielectric, will cause a phase shift in the test voltage, hence the image will appear as an ellipse with an inclined axis as in figure 9*b*. Corona streamers in the dielectric will cause the image to appear as shown in figure 10, while an arc jumping across or through the insulation will change the image to figure 11. A complete short circuit produces a horizontal line as in figure 12*b*.

Conclusion

The data presented in this paper is by no means conclusive. It does not infer that all types of high-potential testing equipment are dangerous to insulating material, nor does it prove that all testing methods are improper. It has brought out the possibility that indefinite surge voltages may exist and that these surges may cause some damage to the insulation. These hazards arise, however, only when some fundamental principle has been violated, such as low- and high-voltage switching. The use of resistance for reducing surge voltages is not new. It has been shown, however, that either low-voltage or high-voltage switching may be employed without creating dangerous surges when the resistance is properly used. Thus, high-speed testing may be conducted to meet any production requirement and at the same time a definite predetermined test voltage can be maintained. There may be other methods of accomplishing the same result, but the resistance control seems to be the most expedient.

The cathode-ray fault detector is a very useful tool in connection with the resistance-controlled transformer. It enables one to determine by a glance, the wave form and magnitude of the test voltage, some of the physical properties of the insulation, and whether or not streamers or corona are present. The voltage which a material will withstand can be readily determined, and unseen flashovers can be detected by careful observation of the screen. If the power arc follows the flashover either momentarily or continuously, it too can be observed. The cathode-ray fault detector may not be practical to use in high-quantity production because of the longer time consumed in making the observations, but it is very useful in laboratory or other work where time is not so important.

Arc-Backs in Ignitrons in Series

J. SLEPIAN
FELLOW AIEE

W. E. PAKALA
ASSOCIATE AIEE

Synopsis: Theory based on the random occurrence of arc-backs indicates that the arc-back rate of ignitrons in series should be very low compared with the arc-back rate of the individual ignitron operating alone on its share of the voltage. To check these ideas, experiments were carried out with high-current ignitrons (350 amperes average per anode) operating in series with voltages balanced and unbalanced, and individually. The results of these tests are given and discussed.

Introduction

THE ignitron is a single-anode mercury-vapor rectifier with a mercury-pool cathode and a stationary electrode, called the ignitor, partially immersed into the cathode pool. A current of a few amperes at about 100 volts passed through the ignitor initiates the arc once each cycle and at any time desired in the cycle. The use of ignitrons with the usual rectifier-transformer connections gives a power-converting system with all the advantages of grid-controlled rectifiers at higher efficiencies, since no grids are required near the anode for the control of load.

In the last few years the use of ignitrons commercially has been greatly accelerated and single assemblies up to 3,000-kw capacity at 600 volts are in service.

Research work continues on the still baffling problem of arc-back. Accepting the arc-back rates as obtained on commercial tubes, however, it seemed desirable to check whether the lower arc-back rate for ignitrons in series, as predicted by the theory of random arc-back could be really obtained.

Two ignitrons were tested in series and individually, at water temperatures abnormally high, and without baffles and shields, so that arc-back rates were high enough for conclusions to be drawn in not too excessive a time. It was found that the two ignitrons in series under these conditions would operate with an average of 13.75 hours per arc-back, whereas an individual ignitron at *half the voltage* would operate with an average of only 0.0442 hours between arc-backs. The calculated value was 16.4 hours per arc-back for the two ignitrons in series.

Test Conditions and Procedure

All tests were made with single-phase full-wave connection from 540-kva transformer bank to two 375-volt, 300-kw d-c machines connected in series. The ignitron tanks were eight inches in diameter with 6-inch graphite anodes $2\frac{3}{4}$ inches from the mercury pool. No grids or baffles were used.

In order to obtain a reasonably rapid arc-back rate for the series operation, and hence not excessively prolong the test, the water temperature was increased

Paper 41-46, recommended by the AIEE joint subcommittee on electronics, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 27, 1940; made available for preprinting December 11, 1940.

J. Slepian is associate director of research and W. E. Pakala engineer for the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

until the arc-back rate was a value which would give rates for series operation of roughly one arc-back per day. It was found that at 700-amperes load and a cooling water-temperature range of 55 begrees to 67 degrees centigrade the arc-dack rate was satisfactory for the test. A current of 700-amperes load is 350 amperes per anode and is not too high for a 6-inch diameter graphite anode.

With conditions as stated above, the ignitrons were operated at 300 volts direct current, one at a time, until ten arc-backs had occurred for each ignitron. These data established the arc-back rate for the individual ignitron for 300-volt operation. Next, the tubes were connected in series and operated balanced (6,000 ohms across each ignitron) or unbalanced (1,000 ohms across one and 75,000 ohms across the other) at 600 volts. After completion of this series test, one ignitron was again operated at 300 volts to check if arc-back rate had changed during the experiment. During this test rates were also obtained for 300 volts by counting breakdowns, on one of the two ignitrons by means of a cathode-ray oscillograph, when the tubes were operating in series at 600 volts with voltages balanced.

The arc-back rate for 600-volt operation of *one* ignitron only was obtained by unbalancing the tubes in series with parallel unequal resistances and counting the breakdowns on the tube which carried almost all of the inverse voltage. From these measured rates at 300 and 600 volts, the arc-back rate for series operation was calculated with the assumption that the arc-back lasts for the whole half-cycle at which it occurs.

Results

The data as obtained in the experiment are compiled in table I. Several counts for the individual ignitrons were made of various durations varying from 5 to 38 minutes. The total time for counting is about the same for the 300- and 600-volt tests. From these data we find that the average time between arc-backs for ignitrons in series is 16.4 hours, when calculated from the arc-back rates of the individual ignitrons, whereas the measured average time between arc-backs is 13.75 hours. These values are for the balanced condition and check reasonably well. For the unbalanced condition, the values are seven hours as measured, and four hours as calculated. The method of calculation is described in the next section.

Discussion

When two ignitrons of the same design are connected in series, the inverse voltage will generally not divide equally between them at all times during the inverse cycle. This unequal distribution of voltage occurs only during the de-ionization time and varies from cycle to cycle. From oscillograms the inverse voltage varied from 600 to 266 volts, immediately after transition, on a single ignitron, in various cycles. This varying unbalance exists, to a continually decreasing extent, for approximately 40 degrees after transition.

To calculate the arc-back rate for ignitrons in series from the arc-back rates of the individual ignitrons, it was assumed that the arc-back cause in the individual tube exists only for the cycle considered, and that complete breakdown of the ignitrons in series will occur, if with an arc-back on one ignitron, one arc-back takes place in the same half-cycle on the other ignitron.

The calculation for the average time between arc-backs for series operation was made as follows:

If

t_3 = average time in seconds between arc-backs at 300 volts, for one ignitron

t_6 = average time in seconds between arc-backs at 600 volts, for one ignitron

f = frequency in cycles per second of power source

t_s = average time in *hours* between arc-backs for series operation

then

$\frac{t_3}{2}$ = average time for one or the other of the two ignitrons when operated in series on 600 volts

After an arc-back occurs in one ignitron, the voltage on the other anode is increased to 600 volts and its individual arc-back rate is increased. The time in cycles between arc-backs under this new condition is for one ignitron only, since we are considering that two in series are used, and we have t_6f as the number of cycles between arc-backs. The product of the above factors gives the average over-all arc-back free time for two ignitrons connected in series and in terms of hours.

$$T = \frac{ft_3t_6}{2\times 3{,}600} \text{ hours}$$

and for 60-cycle power source

$$T = \frac{t_3t_6}{120}$$

hours between arc-backs for the balanced condition. This equation was used to determine the arc-back free time for series operation after t_3 and t_6 had been measured.

For the unbalanced case, t_6 is used twice and since the voltage before an arc-back is practically zero on one of the

Table I

Ignitron	Resistance Across Other Ignitron	Volts	Amperes	Time of Count in Minutes	Number of Arc-Backs	Average Time Between Arc-Backs in Seconds T
3A48-2	None	300	700	21	6	210
3A48-1	None	300	700	25	7	214
3A48-2	None	300	700	38	10	228
3A48-2	6,000	300	700	19	26	46
3A48-1	6,000	300	700	10	5	120
3A48-2	6,000	300	700	10	4	150
	6,000	300	700	8	6	80
3A48-2	1,000	300	700	15	4	225
For 300 volts average time between arc-backs = 159 seconds						
3A48-2	6,000	600	700	14.5	207	4.2
3A48-1	6,000	600	700	15	61	14.8
3A48-1	1,000	600	700	14	100	8.4
	1,000	600	700	8	72	6.67
3A48-2	1,000	600	700	32	66	29.0
3A48-1	1,000	600	700	19	136	8.4
3A48-1	1,000	600	700	5	0	Water 33 degrees to 40 degrees centigrade
3A48-2	1,000	600	700	7	23	18.3
3A48-1	1,000	600	700	7	20	21.0
3A48-1	1,000	600	700	10	31	19.4
3A48-1	1,000	600	700	16	72	13.3
3A48-2	1,000	600	700	12	24	30.0
Average time between arc-backs at 600 volts = 15.8 seconds						

NOTES: Measured average time between arc-backs for two ignitrons in series and balanced was 13.75 hours (Test time was 55 hours.) Calculated from data:

$$\frac{159\times 15.8}{120} = 21 \text{ hours}$$

Calculated with first three values of table I omitted:

$$\frac{124\times 15.8}{120} = 16.4 \text{ hours}$$

Measured average time between arc-backs for two ignitrons in series and unbalanced was 7 hours. (Test time was 21 hours.)

Calculated from data:

$$\frac{15.8\times 15.8}{60} = 4 \text{ hours}$$

Electrolytic Process of Scale Removal From Steel

H. W. NEBLETT
MEMBER AIEE

ELECTROLYTIC action is by no means new or unfamiliar. It is as old as electricity itself and has been evidenced in many ways throughout the entire application and use of electricity. One of the early applications of electrolytic action pertaining to metals was employed in the refining of copper and similar metals. Also, electrolytic action was employed in the plating of metals on surfaces requiring a high finish or protective coating, which, of necessity, should be very thin. This application is best evidenced in nickel plating and chromium plating which has been widely used for a number of years.

Electrolytic action has been in general use in steel mills and other industries for cleaning steel sheets, for example, the hot caustic electrolytic scrubbing equipment for removing oil and dirt from cold-rolled sheets. This application of electrolytic action is used in conjunction with mechanical scrubbing and brushing rolls for cleaning the sheets, the electrolytic action being a primary and the scrubbing action the secondary means for obtaining this result. It, therefore, may seem strange that this very familiar and well-known principle of electrolytic action which has been in wide and rather diversified use for so long a time has not been applied to pickling or the removal of scale from steel in a sulphuric acid bath.

The answer to this, we believe, is due to the physical and mechanical difficulties encountered when trying to apply electrolytic action in a sulphuric acid bath. There are many physical difficulties encountered when a combination of electrolytic action and sulphuric acid pickling action are combined. This can be readily understood when it is realized that electrolytic action in combination with sulphuric acid is decidedly destructive to any current-carrying metal such as nickel, copper, aluminum, or steel. Also, sulphuric acid is an active agent in decomposing some of these materials, particularly steel. Therefore, the reluctance in applying electrolytic action to the pickling of steel which involves the use of sulphuric acid, has, no doubt, largely been due to these physical difficulties encountered rather than a lack of appreciation of the benefits derived from such an installation.

Development

In the processing of flat-rolled steel, it is necessary to remove the mill scale and oxide from the entire surface of the steel which is usually produced in coils of various widths and lengths. To remove the mill scale from these coils of steel, the normal procedure is to run the strip steel through a continuous pickling line which consists of a series of tanks arranged in tandem, filled with approximately a ten per cent solution of sulphuric acid and provided with the necessary mechanism to permit the strip steel to be uncoiled and fed through the pickling line in a continuous strip, the strip being delivered at the finishing end with the scale removed by the action of the sulphuric acid in which it has been submerged. Any practical application of electrolytic action which might be used in augmenting or improving the pickling action described above, should be applied to the existing continuous pickling line and would take the position of being additional apparatus applied to this already standard equipment.

On account of the physical difficulties mentioned above, it would therefore follow that considerable experimentation would be required to develop a feasible working assembly of equipment that would have commercial application in a continuous pickling line. With this viewpoint in mind, a number of years were spent in experimenting and developing this electrolytic equipment. Early experiments were made to determine the feasibility of using either direct or alternating current, and it was found that practically equally satisfactory results could be obtained with either of these currents.

Another problem was the method of applying the current to the sheet of steel which was to be pickled, bearing in mind that since this sheet steel is being continuously fed through the pickling line, it would be necessary that any current-carrying device that made contact with the strip would have to be in the form of a roller or some similar contacting device. This, in itself, presents quite a problem, as the contacting medium would be submerged in a sulphuric acid bath and would also be carrying electric current. This naturally would result in the contact

Paper 41-77, recommended by the AIEE committee on electrochemistry and electrometallurgy, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 26, 1940; made available for preprinting December 18, 1940.

H. W. Neblett is engineer for the Inland Steel Company, East Chicago, Ill.

1. For numbered reference, see end of paper.

---

tubes, it is not necessary to divide by two, as was done above. The arc-back free time for the unbalanced case will be

$$T=\frac{t_6 t_6}{60} \text{ hours}$$

Following table I the calculations are shown for the two cases. In the balanced case two values are given; namely, 21 hours and 16.4 hours. In obtaining the latter value, the first three values of table I were omitted. It is believed that they are high because the time ignitrons were "off the line" after each arc-back is an appreciable fraction of the operating time. This allows the tubes to cool somewhat, and higher times may, therefore, be measured. Also the unbalance due to ionization variation made these three tests of uncertain value.

When the ignitrons were connected in series and the parallel resistance across an ignitron was 1,000 ohms, an arc-back in an individual ignitron, as determined by the cathode-ray oscillograph, would continue to the end of the half-cycle at which it started. However, with 6,000 ohms an arc-back would often clear before the end of the half-cycle. This instability is characteristic of arcs when the current is limited.

Conclusions

Experiments verify that the arc-back rates of ignitrons operated in series can be calculated from their individual arc-back rates. This indicates an advantage in direct series operation of ignitrons for high voltage, rather than placing ignitrons with their associated transformers in series.

material being eaten away rather rapidly by the electrolytic action and, in most cases, would result in depositing a coating of this material on the strip steel which is to be pickled.

From experimentation, it was found that the amount of current necessary to obtain proper electrolytic action in the removal of scale was from 100 amperes to 150 amperes per square foot of the strip steel being pickled. This large amount of current, if applied directly to the steel strip, would require contact rolls at frequent intervals throughout the length of the steel strip to equally distribute the current over the entire surface of the steel. Due to the difficulty encountered in applying the current in this way, it was decided to place current-carrying electrodes in the pickle bath, these electrodes being spaced on either side of the steel strip top and bottom, the strip allowed to pass through the sulphuric acid pickling bath between these electrodes. Then, by applying alternating current to these electrodes, the current would continuously pass back and forth between the electrodes and, in so doing, would pass through the sheet, in this way setting up an electrolytic action on the sheet materially assisting in the removal of the scale. This scheme was adopted and top and bottom electrodes, spaced apart, were installed in the pickling tanks and means provided for carrying the strip continuously through the tank between these electrodes.

The next consideration was the proper material to use in forming these electrodes. Considerable experimentation was carried on in this matter and, after trying out many different materials, it was found the most satisfactory material was graphite slabs which could be made up into electrodes of any required size by the assembly of these slabs into a unit of the required dimensions. Each pickling tank is approximately 60 feet long and of a width sufficient to allow the passage of the widest steel strip, which means that these tanks, in some cases, are eight feet wide. Since it was important that the electrolytic current be, as near as possible, uniformly distributed throughout the entire length of the submerged sheet, it was decided to install a number of electrodes in each tank rather than a single top and bottom electrode which would extend the entire active length of the tank. Consequently, these electrodes were designed to a dimension that would correspond to the width of the tank and allow a multiple number of electrodes to be installed throughout the length of the tank. This resulted in a final selection of six top and six bottom electrodes being installed in each pickling tank. The actual dimensions of these electrodes, in our case, were about four feet two inches wide and six feet six inches long and were installed in a pickling line that was designed for accommodating a maximum width steel strip of 44 inches.

To further insure uniform distribution of current, means were provided for bringing current into each electrode at four points. Each pickling tank was supplied with current from two transformers, each transformer feeding one-half of the electrodes in a tank. This results in a minimum length of current-carrying conductors between the transformer and the electrodes. This is an important factor to be considered when dealing with current flow of this large amount and low voltage.

The voltage required to pass the amount of current necessary through the pickling solution varies with the strength of the sulphuric acid and the content of the iron sulphate in the solution. Therefore, transformers were provided with a five-point tap changer on the primary side which would give a secondary voltage range from 15 volts down to 7 volts. The transformers were also provided with three segregated secondary windings, each winding connected direct to one top and one bottom electrode. This was done to further insure the uniform distribution of the current to the strip steel being pickled. The lower or seven-volt tap of the transformers is used when the pickling bath is first put in use, which means that there is at least ten per cent sulphuric acid solution and no iron sulphate. As the pickling action progresses, the acid is consumed resulting in a gradual lowering of the acid in the solution. Also, since the pickling action will remove a small amount of steel from the sheet, along with the scale, there will be gradual build-up of iron sulphate in the solution. These two conditions result in increasing the electrical resistance of the pickling solution which necessitates increasing the voltage to compensate for the increased resistance. This accounts for the various voltage taps mentioned above.

It is necessary to provide some means for controlling the current supply to the electrodes which is synchronized with the feeding of the strip through the pickling tanks and so connected that the electrolytic power is on only during the operation of the pickling lines and automatically shut off each time the line is stopped. This is necessary to prevent the pickling action continuing while the strip is not in motion. If this precaution was not taken, it would result in the strip being overpickled each time the line is momentarily stopped. In addition to this automatic control, there is also provided a manual control on the pickle line operator's control pulpit board.

Electrolytic action is most active after the sulphuric acid solution has penetrated through the film of scale and has reached the steel surface of the sheet. For this reason, the first tank in a continuous pickling line is not provided with electrodes, this tank being used as a conditioning tank which will allow the acid to penetrate through the film of scale. The electrodes are installed in the second and third tanks only in which the entire electrolytic action is applied and where the major part of the scale is removed. The fourth or last tank in the continuous pickling line is used only as a clean-up tank which will remove any remaining particles of scale still adhering to the steel strip.

The terminals connecting to the top and bottom electrodes carry a heavy current and it is necessary that they be well insulated to prevent current leakage and electrolytic action on these conductors. The insulating material used should be able to stand up under the action of hot sulphuric acid and acid vapor. Good grades of rubber will give very acceptable service in acid or vapor, with temperatures not exceeding 125 degrees Fahrenheit. The temperature of the pickling solution in a continuous pickling line is approximately 190 degrees Fahrenheit. At this temperature, the life of rubber is greatly reduced, therefore it is not entirely satisfactory in this service.

After considerable experimentation, we found that a glass fabric tape, impregnated with one of the synthetic insulating compounds such as Koroseal would give very satisfactory results, and this is the type of insulation that has been employed. In some of these cases, rubber is first applied to the conductors and then the glass fabric tape applied over the rubber. In others, it is applied directly to the conductor, and both installations have proved entirely satisfactory.

The steel strip forms a catenary in each pickling tank being supported on rollers in the end of each tank and allowed to dip down into the pickling solution. When electrodes are installed above the strip, it is necessary to provide some means to prevent the steel from coming in contact with the top electrodes as it travels through the tanks. Hold-down rollers were installed at each end of the electrodes in each tank. These rollers are

required to operate submerged in the acid solution and are subjected to the combined effect of hot sulphuric acid, iron sulphate, electrolytic action, and mechanical wear and shock. Materials that will stand up indefinitely in sulphuric acid, such as bronze and monel metal, will be dissipated in a very few hours when subjected to electrolytic action. Bearings have to operate submerged with no lubrication other than that of the hot sulphuric acid. These conditions are rather severe for any material that would provide a satisfactory hold-down roller.

However, a roller assembly has been developed which stands up well and gives long life and service. This consists of a roller with an extended shaft made from either carbon or a dense, compact compound using a resin base and asbestos binder. To the shaft of the roller are fitted Pyrex glass bearings. The rollers are held in position in the tanks by means of steel pipe arms which are covered with rubber, around which is applied an outer wrapping of glass fabric tape which has been impregnated with a synthetic compound. The glass bearing is fitted into a bearing housing supported by these pipes, the housing being made from the same material as the roller. This type of roller has given very satisfactory service during several years of use.

Operation

An electrolytic pickling unit, in our case, is installed on one of three continuous pickling lines.[1] This particular line is one that normally handles coils of comparatively thin gauge, narrow width, and considerable length. Due to this condition a greater speed is required on this line to produce a given tonnage in a given time than is required in the case of the other pickling lines which handle wider and heavier materials. This is the reason for the selection of this particular line to be equipped with electrolytic equipment.

The handling of coils in the feed end of a pickle line including leveling, shearing, and welding or stitching, requires a given amount of time regardless of the length of the coil. Therefore, a long coil lends itself more readily to the use of electrolytic pickling equipment than a short coil. For example, assuming a normal pickling speed of 100 feet per minute and a coil length of 200 feet: in this case, it will require two minutes for the entire coil to pass through the pickling bath. If two minutes are also required to place a new coil in the feeding equipment and perform the necessary operations such as leveling, shearing, and welding, the time of the two operations balance and there is no necessity for installing electrolytic pickling equipment in order to increase the pickling speed which is limited by the feeding operations. On the other hand, assume that the coils are available twice the length specified, or 400 feet and since the feeding time would be the same regardless of the length of the coil, electrolytic equipment could be installed to advantage, as the feeding operation would permit, in this case, a pickling speed as high as 200 feet per minute. Therefore, it is readily seen that the length of coil available has an important bearing on the advisability of applying electrolytic equipment in order to obtain additional pickling speed.

In any continuous pickling line there will be found a large variation in pickling speeds. A given line may, at times, operate at a speed of 120 feet per minute and at other times may be able to remove the scale and do a perfect pickling job on the steel at 200 feet per minute. This wide range of pickling speed is due to a number of factors, such as coiling the steel hot, or somewhat cooled before coiling in the hot mill, coils stacked hot and allowed to cool before pickling, or coils being pickled while still fairly hot, high phosphorus or high carbon steel. There are also other factors that affect the pickling speed, such as the strength of the sulphuric acid solution in all or part of the tanks, and the presence or lack of iron sulphate in the pickling tanks. Any one of these factors has an effect on the speed of pickling and when a combination of a number of these factors is present, a low pickling speed will result, and ideal conditions will naturally produce the higher pickling speeds. Therefore, these conditions also have to be given consideration in considering any means relative to increasing the pickling speed of a continuous pickling line.

Any increase in speed of pickling due to electrolytic action over what can be obtained without it results in a direct increase of tonnage from the line. This tonnage is realized with no increase in labor or overhead. The only additional cost of this tonnage is the interest on investment of electrolytic equipment, its maintenance, and the cost of the current consumed. Our experience over a number of years shows that we obtain an average increase of 35 per cent in tonnage with the electrolytic equipment over what would be obtained in this same pickling line without the use of electrolytic. The electric load for the electrolytic pickling equipment is 600 kw.

When considering the interest on investment, the maintenance, and the cost of the current consumed, it is found that the cost of pickling chargeable directly to the additional tonnage that is realized due to the operation of electrolytic equipment is considerably lower than the normal cost of pickling a ton of steel without electrolytic equipment. Therefore, under the proper conditions, electrolytic equipment shows a decided saving.

Electrolytic equipment installed on a continuous pickling line will increase the speed of the line regardless of the type of scale, the amount of scale-breaking equipment, or the grade of steel being pickled. To realize the full advantage of this increase in speed and to actually secure an increase in tonnage, the pickling line must be able to operate in the time required for a coil to pass through the pickling bath at the higher speed that can be obtained from the use of electrolytic action. Under this condition an electrolytic installation will show a good return on investment. If this condition does not exist, the time saved by the use of electrolytic equipment will be offset by the delay due to preparing a new coil for feeding into the pickling line.

The handling and feeding of coils into pickling lines is constantly being speeded up. More efficient coil handling and processing equipment is being provided by the equipment manufacturers. The time required to weld and trim coils is also being steadily decreased, all of which results in the cutting down of the time required to deliver the coil to the pickling line. This creates a condition receptive to any means that will result in a faster pickling of strip steel and electrolytic pickling equipment has a most feasible application under these conditions as a definite means of securing increased production from a pickling line.

Reference

1. For complete description see Electrolytic Pickling of Strip Steel, H. W. Neblett. Association of Iron and Steel Engineers Yearly Proceedings for 1939, page 188.

Enclosed Bus-Bar Electrical Distribution Systems for Industrial Plants

E. T. CARLSON
ASSOCIATE AIEE

Introduction

ENCLOSED bus-bar distribution systems have come into common usage to meet the needs of industry for the greater availability of electrical power in production areas. Beginning in 1927 the automotive industry pioneered the application of enclosed bus-bar systems as a solution to the frequent recurring problem of modifying the electrical distribution system incidental to mass production changes. Since that time there has been an increased utilization of bus-bar systems by all branches of industry.

It is the purpose of the author to present in this paper a review of the fundamental electrical characteristics of such systems, discuss and describe some typical applications, and to emphasize the need for further fundamental research to meet the growing demands of industry.

The nature of industrial application requiring economy, safety, and compactness, brought about commercial designs using formed metal enclosures, porcelain or cold-molded insulating supports, and closely spaced copper and aluminum bus bars. The common industrial voltages for which commercial designs are being manufactured are: 120/240 volts, single phase, and 120/208 volts, three phase, four wire, for light; and up to 600 volts, three phase, for power.

The industrial applications of enclosed bus bars are for main feeders generally in current ratings up to 4,000 amperes, and for obtaining convenient outlets for power in current ratings, from 125 to 1,000 amperes. Both types of products are classified as "busways" in the National Electric Code, but in this paper the two types will be differentiated by the terms "feeder busways" and "plug-in busways."

Paper 41-64, recommended by the AIEE committee on industrial power applications, and presented at the AIEE winter convention, Philadelphia, Pa., January 27-31, 1941. Manuscript submitted December 2, 1940; made available for preprinting December 13, 1940.

E. T. CARLSON is manager of The Trumbull Electric Manufacturing Company, Inc., Norwood, Ohio.

Grateful appreciation is extended to Y. T. Chaney for his assistance in the preparation of this paper.

1. For all numbered references, see list at end of paper.

While enclosing bus bars in switchboard structures, bus-bar cell construction in central stations, and interconnecting busses between equipment has been common practice for years the experience and empirical data and studies made of these bus-bar applications were not as helpful as anticipated. This is explained by the fact that these designs were of rectangular bus bars on comparatively wide spacing, and in large enclosures.

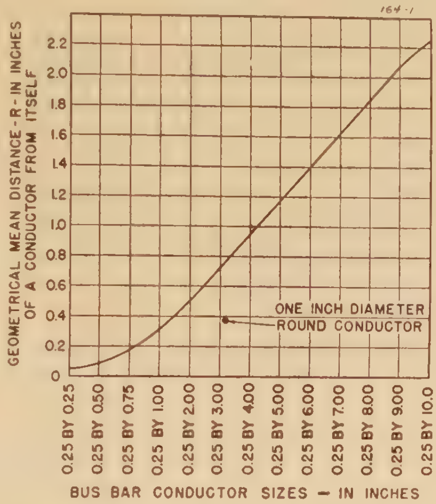


Figure 1. Geometrical mean distance of a bus bar from itself

As in all electrical distribution systems the important factors to be considered in planning a busway system are: voltage regulation, temperature rise, and mechanical design. The fundamental approach to the application of busways requires a determination of the impedance per unit length and current-carrying capacity of the selected design.

Voltage Regulation

Knowing the characteristics of a unit length of a selected design, the specified voltage regulation of a busway system, as for other distribution systems, is obtained by the usual series and parallel circuit connections.

Unfortunately, at present, specific unit length characteristics of busway systems are not as available in literature as for cable systems. One of the factors which contributes to this situation is that in meeting the increasingly exact service requirements of industry, the manufacturers have continued a process of evolution which in itself has not given encouragement to the publishing of tables and data. A second contributing factor is that in the tendency to closer and closer bar-to-bar spacing, skin and proximity effects become of increasing importance and must be studied more carefully than in the past, if exact resistance and reactance values are to be made available, for the multitude of conductor combinations now required by industry. Bar face-to-face spacings of the order of a fraction of an inch are not unlikely.

Assuming a uniform current distribution in each bar, that is neglecting skin and proximity effect, which has been rather common practice, the inductance of a rectangular bus-bar system may be determined from the scientific papers of E. B. Rosa and F. W. Grover.[3,4] This work gives the approximate self inductance of a straight cylindrical wire as:

$$L_s = 2(l)\left(\log_e \frac{2l}{\rho} - 1 + \frac{\mu}{4}\right) \tag{1}$$

And the approximate mutual inductance between two parallel cylindrical wires as:

$$L_m = 2(l)\left(\log_e \frac{2l}{d} - 1 + \frac{d}{l}\right) \tag{2}$$

And the approximate net total inductance per wire of a two-wire transmission line as:

$$L = 2(l)\left(\log_e \frac{d}{\rho} + \frac{\mu}{4} - \frac{d}{l}\right) \tag{3}$$

where

l = length of wire
d = center-to-center separation of wires
ρ = radius of wire
μ = permeability of medium

When the length (l) of the wire is great in comparison with the spacing (d) the last term (d/l) of this equation may be neglected.

For a nonmagnetic cylindrical tube of infinitesimal thickness or for high-frequency circuits, where no magnetic field exists within the conductor then the second last term ($\mu/4$) may also be neglected. This condition is not always met in industrial power distribution practice and the ($\mu/4$) term (with $\mu=1$) should remain in the equation. This term represents the self inductance due to the flux within the conductor itself and is a factor of considerable relative importance on close spacings.

When other than a straight cylindrical wire is employed as for example the rectangular conductor in a busway, it is convenient to use modifying factors to convert the dimensions of the conductor arrangements into that of an equivalent cylindrical wire system in order to utilize the above fundamental inductance relationships.

The most acceptable modifying factors in use at the present are those based upon the concept of geometrical mean distances introduced by Clerk Maxwell.[1] Later F. W. Grover[4] published tables and data for calculating the inductance of rectangular conductors, in which the following definitions appear. "The geometrical mean distance (gmd) of a single area is that distance whose natural logarithm is equal to the average of the natural logarithm of the distances of all points of the area from each other." For a rectangular area of thickness a and width b an approximate expression of self-geometrical mean distance is:

$$R = 0.2235(a+b) \tag{4}$$

where R = self-geometrical mean distance.

"The geometrical mean distance of two areas is that distance whose logarithm is the average of the logarithms of the distances of all the points of one area from all the points of the other." If D equals the geometrical mean distance of two areas and d the center-to-center distance between these areas then:

$$D = kd \tag{5}$$

or

$$\log_e D = \log_e k + \log_e d \tag{6}$$

Value of the $\log_e k$ for equal parallel rectangular areas are given in tables by Grover. Doctor O. R. Schurig[13] further simplified the solution of mutual geometrical mean distance by a graph published in his article on the calculation of inductance for rectangular bar conductors.

If the current distribution within each conductor is uniform these geometrical mean distance factors, as discussed by Rosa and Grover, can be substituted in equation 3, R for ρ, and D for d, as follows:

$$L = 2(l)\left(\log_e \frac{D}{R}\right) \times 10^{-6} \text{ millihenrys per centimeter} \tag{7}$$

Note that $\mu/4$ turn does not appear in equation 7 since the flux within the conductor is taken into account in the determination of the gmd, and nonmagnetic conductors are assumed. C. C. Levy[12] discussed this point in his article "Calculation of Inductance and Current".

Examples of the geometrical mean distance factors R and D for a range of one-fourth-inch copper bus bars versus conductor spacing are given in figure 1 and figure 2 respectively. Applying these factors to equation 7 the calculated 60-cycle reactance for a wide range of one-fourth-inch bar widths is shown in figure 3. The values in figure 3 are for uniform current distribution.

It is well known, however, that the current distribution within large conductors is not uniform and therefore the geometrical mean distance factor modifications are not strictly accurate. If the current is crowded to the ends and sides of a rectangular conductor due to skin effect and if the crowding effect is made asymmetrical due to proximity effect, then this current distribution pattern is important in the determination of the flux linkages of self and mutual inductance. Further research should be encouraged to determine factors applicable to commercial bus structures, particularly for closely spaced multiple interleaved conductors. It is not only the value of inductance that is important but also the effect upon the current-carrying capacity of the conductors. This will be discussed later in the paper.

Another factor entering into the design of a commercial busway system for a specified voltage regulation is the voltage unbalance between the phases. If the conductor arrangement differs from an equilateral triangle then the individual phase voltages must be calculated and if necessary the phase conductors transposed at intervals along the busway. The problem is often identical to that of a flat transmission line. This unbalance in the induced voltages of the respective conductors is due to two factors: difference in reactance between the respective phases and the 120-degree displacement of the current in the three phases. Fortunately, it is a simple matter to make transposition in most modern busway systems and thereby attain balanced voltages.

In figure 4 are shown phase-voltage readings along an early wide-spaced (five-inch center to center of bars) high reactance, flat facewise configuration busway installation before and after transpositions were made. Present-day closely spaced designs would produce the same relative characteristics, but with voltages of much improved regulation.

Power-factor correction static condensers are often located along the lines of a busway system to take full advantage of improved voltage regulations along with power-factor correction.

In these early systems as well as in many installations of today, reactance plays a dominant part in the impedance drop, while as spacings are made closer, the resistance component becomes increasingly important and may even itself become dominant. Here again, the importance of skin and proximity effect enters into voltage regulation calculations, this time by increasing the a-c resistance.

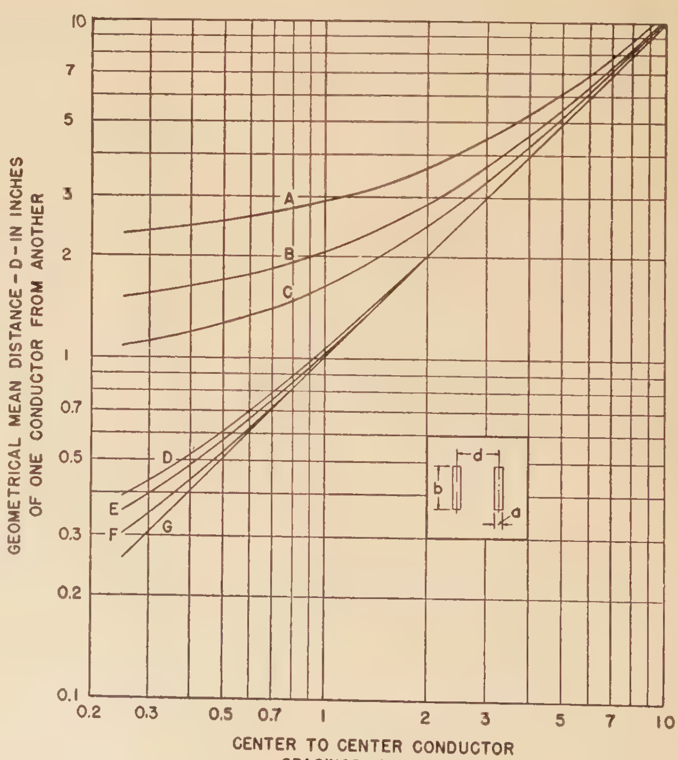


Figure 2. Mutual geometrical mean distance versus spacing for two rectangular bus bars

Designation of bus-bar sizes on curves, all bar dimensions in inches:

A—0.25 by 10
B—0.25 by 6
C—0.25 by 4
D—0.25 by 1
E—0.25 by 0.75
F—0.25 by 0.50
G—0.25 by 0.25

Current-Carrying Capacity

While skin effect causes a higher density in the outside periphery of a conductor, proximity effect has the tendency to crowd the current to the outside when currents flow in the same direction in adjacent conductors and to the inside when currents flow in the opposite direction in adjacent conductors. In certain cases, therefore, proximity effect may in combination with skin effect, actually cause a better distribution of current and, therefore, a lower a-c resistance than results from skin effect alone. On the other hand, these two effects more often combine to produce a considerably greater a-c resistance. Tests have shown this increase in resistance to be very significant. A more comprehensive knowledge of these combined effects will prove beneficial in the accurate establishment of the current ratings of bus-bar systems for a given temperature rise. Limited investigations seem to point to the importance of symmetry where several conductors are connected in parallel.

When bus bars are spaced closely, phases connected in parallel and interleaved as in figure 5, more research and study will be required before an accurate prediction can be made of the system's voltage regulation, power loss, and current-carrying capacity.

It is present commercial practice to rate bus systems arbitrarily on the basis of 1,000 amperes per square inch, despite the fact that this system of rating does not result in a uniform temperature rise for the respective sizes at rated load.

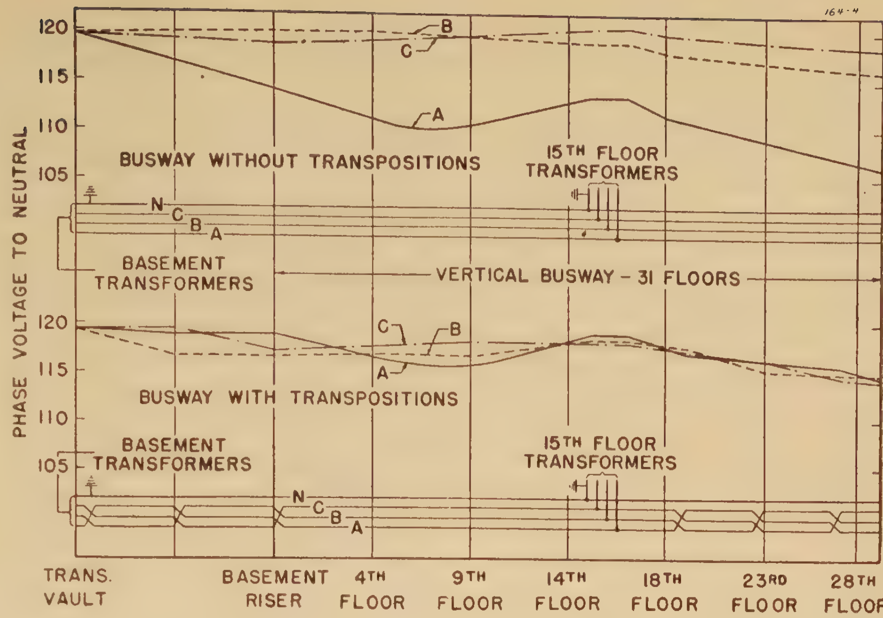


Figure 4. Voltage regulation of the respective phases along a three-phase, four-wire wide-spaced early type busway design before and after making transpositions

Progress is being made, however, toward a more accurate rating of the bus systems through the co-operation of manufacturers with the underwriters. In the meantime, the manufacturers simply provide the necessary capacity to carry the load for the specified temperature rise.

Another and very important factor in the modern busway system is the design of its protective enclosure. The present practice is to make these enclosures of steel for ratings below 1,500 amperes, and of nonmagnetic material for high-current ratings.

Housings of nonmagnetic materials are often preferred to steel for certain high-current rating designs because of the high-flux densities and eddy currents induced in the steel housings which give rise to excessive temperature and voltage drops.

Various means are employed for ventilating the housing and cooling the enclosure by convection, but in general, the enclosed system will not have as high a current-carrying capacity for a given temperature rise as will bars in the open air. Industry, of course, realizes this

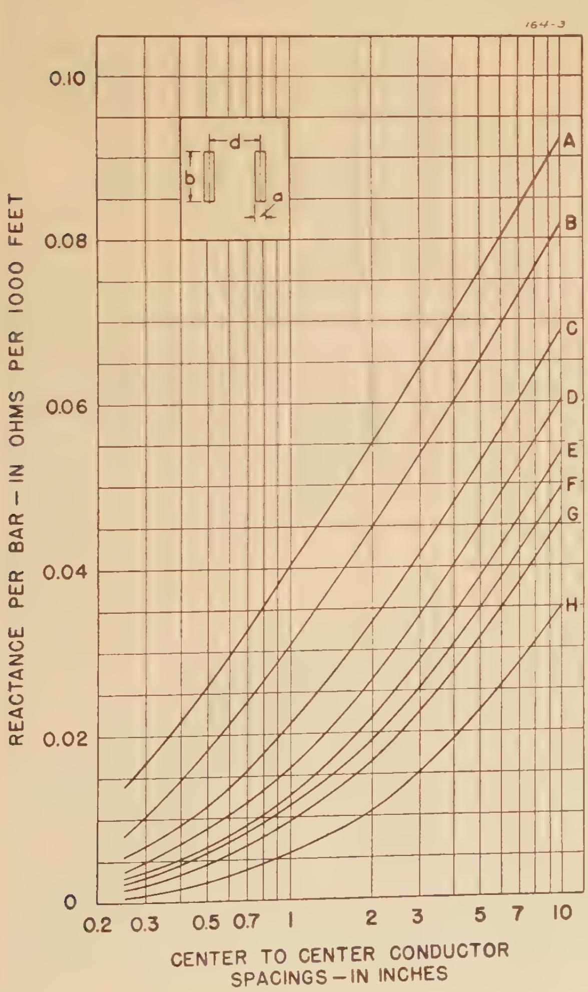


Figure 3. Reactance per bar versus spacing for two rectangular bus bars

Designation of bus-bar sizes on curves, all bar dimensions in inches:

A—0.1875 by 0.625
B—0.25 by 1
C—0.25 by 2
D—0.25 by 3
E—0.25 by 4
F—0.25 by 5
G—0.25 by 6
H—0.25 by 10

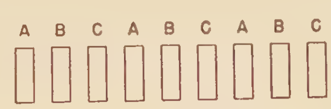


Figure 5. An example of parallel interlaced three-phase rectangular bus-bar conductors

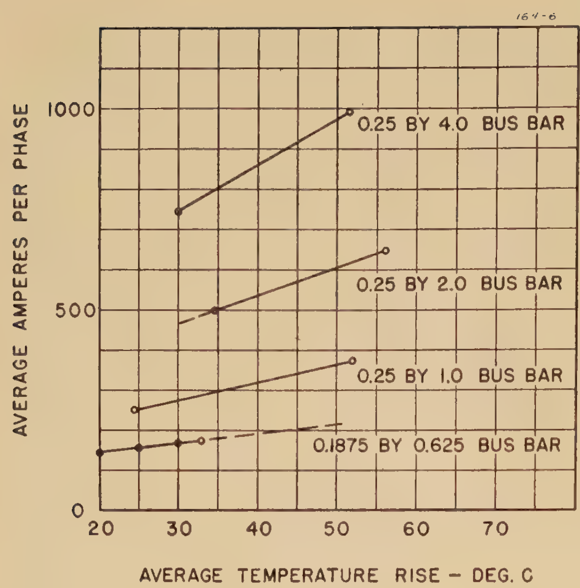


Figure 6. Test data on current versus temperature rise of three-phase, three-bar, 60-cycle plug-in busways. Bus bars of copper. Dimensions in inches

situation and accepts the lower capacity of the enclosed system because of its obvious other advantages. The actual rating of an enclosed system in the final analysis, probably, will be based upon tests of the particular design. In general, it is the same problem as encountered in the operation of a number of cables in a duct enclosure. An example of the carrying capacity of some typical busway systems is shown in figure 6.

Applications

It is interesting that the earliest industrial electrical distribution systems had open feeders extending the length of the plant, with ceiling-mounted link-fuse protection of tapoffs for individual power loads, similar to the fundamental concept of modern busway systems. The fire and personal injury hazards of the materials then available brought about the alternative practice of radiating conduit and wire feeders from a main switchboard or from several subdistribution centers.

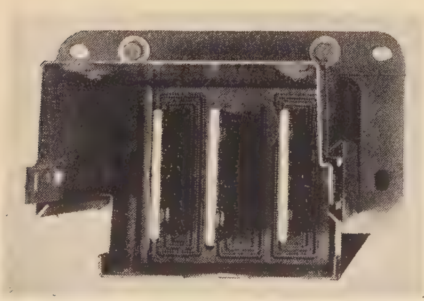


Figure 7. End view commercial design plug-in busway

1/4- by 4-inch rounded edge bars. Insulator one-piece porcelain. Enclosure assembly of formed steel sheets

The radial system met industry's needs through the early decades of this century, but with the advent of mass production, individual motor drives, expanding and changing load centers, the static nature of the radial system often resulted in overloaded feeders and equipment, poor voltage regulation, and costly rearrangement expenditures. A system which would provide the same convenience for power in industry as plug receptacles do in the modern home, became industry's demand.

Plug-in Busways

This need of industry for a greater convenience of power is being met by manufacturers with a system of power and light plug-in devices which engage bus bars supported within a metal enclosure.

The complete system for an industrial plant usually consists of a number of overhead parallel busway runs located according to machinery concentrations, plant conditions, and column centers. These bus structures are usually located overhead and supported by building structural members. An exception to this method of supporting the busway is shown in figure 10 which is a photograph of an installation in a high bay crane area where suspension means of support could not be used.

Connections are made to the busway circuits by the insertion of combination plug-in switch and protective devices at such points as to provide the most economical branch circuit layout. A section of a typical busway run with plug-in device in position is shown in figure 8. The arrangement of bus bars and construction details of a typical busway type of enclosure with its insulator assembly is shown in figure 7. Branch circuits are extended from the plug-in protective device by the customary wiring method to the individual power equipment drives or distribution centers. Such an example is shown by the photograph in figure 11.

The growing need for the installation of static condensers to correct for low power factor has led to the design of plug-in capacitors which correct for power factor and improve the voltage regulation on the busway. The location of these capacitors, of course, depends upon the characteristics and distribution of the load, but as a rule, a location near the load end of the busway provides best results. A photograph of a typical

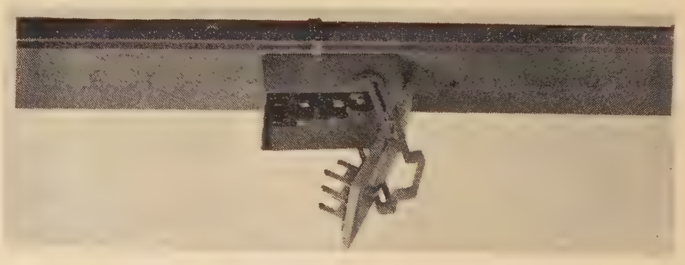


Figure 8. Protective device engaged to plug-in busway through one of the enclosure outlets

Load conduits are extended from knockouts in protective devices

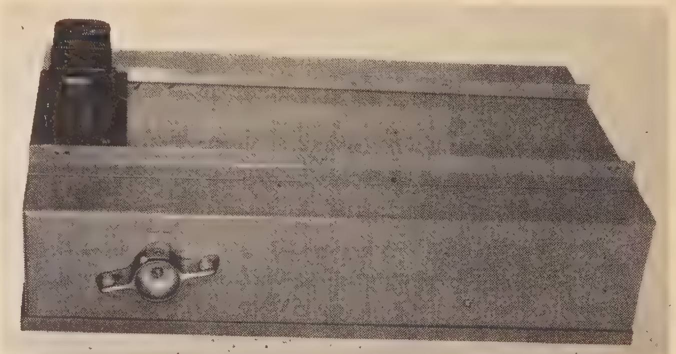


Figure 9. Combination plug-in protective device and capacitor

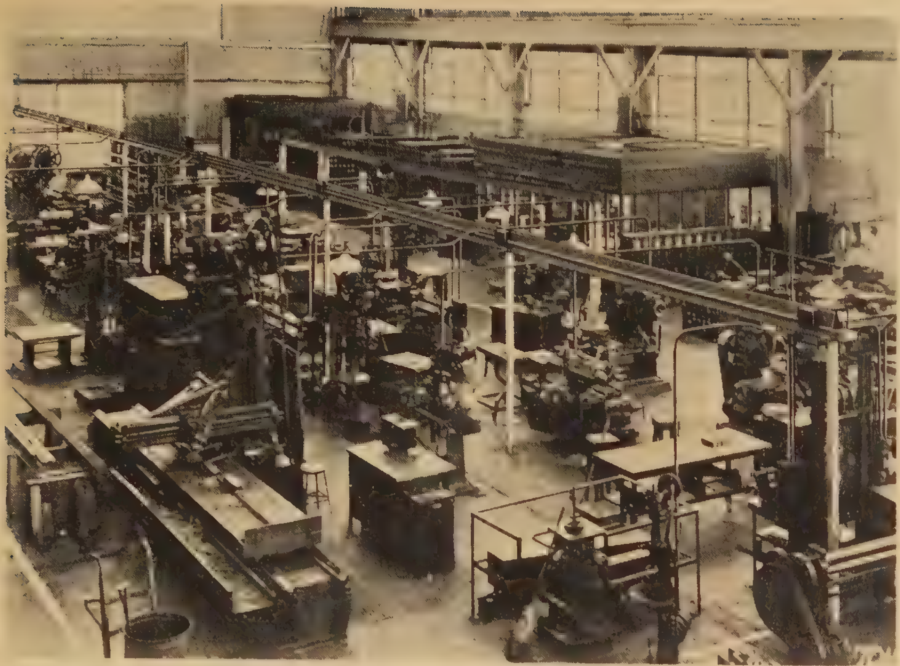
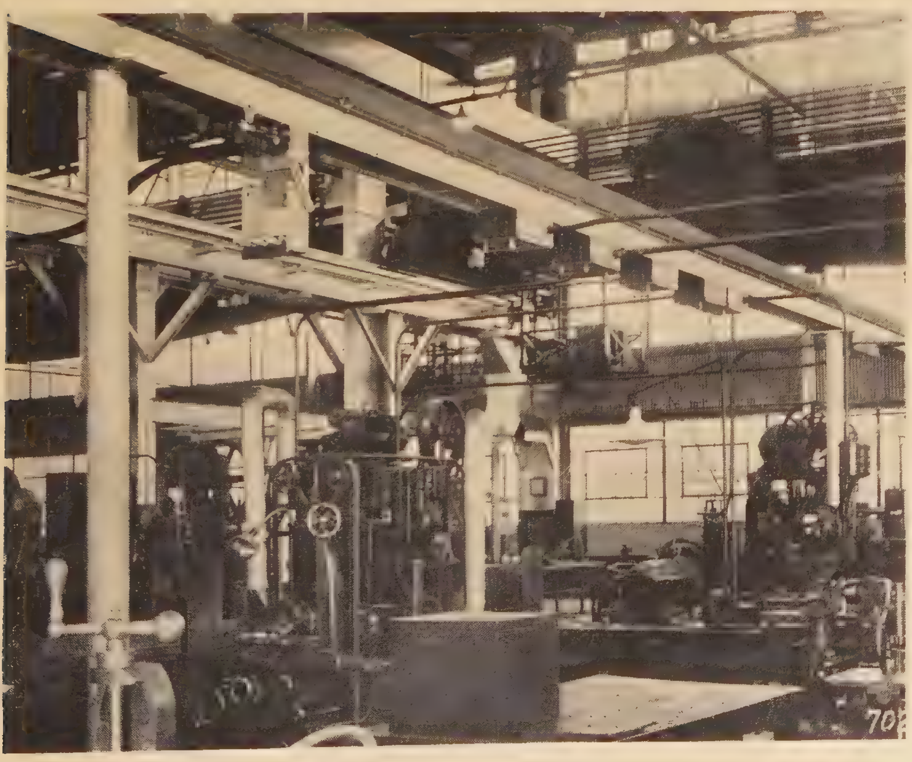


Figure 10. Plug-in busway system supported by iron pipe uprights spaced on 20-foot centers for supplying power to motors in high bay crane area

plug-in capacitor is shown in figure 9.

The common industrial application of busway plug-in systems is to 440-volt, three-phase, three-wire, 60-cycle a-c power distribution, although there is an increasing acceptance of the plug-in busway for three-phase, four-wire combination light and power systems. Where light is supplied from a busway it is general practice to extend conduit and wire circuits from plug-in equipment to lighting distribution panel boards or transformers. Where there is a need for an even more flexible supply of power to portable tools, such as along an assembly line, it is the practice to install a trolley collecting device supported on a track which is an integral part of the bus-bar enclosure.

Figure 11. A close-up view of layout, figure 10, showing protective devices and branch motor circuits



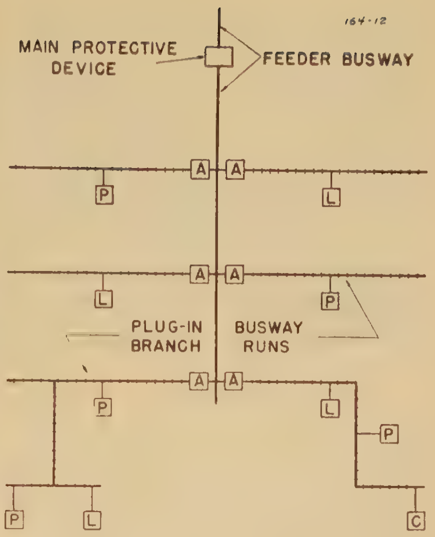


Figure 12. Schematic layout of a busway system frequently used in industrial plants

Symbols indicate protective devices for the following applications:

P—Power loads
L—Light loads
A—Branch plug-in busway
C—Capacitors

Plug-in busways may be supplied with power directly from distribution centers, by conduit and cable wiring methods, or by a feeder type of busway.

Feeder Busway

Feeder busways differ from the plug-in type in that they are generally of higher current-carrying capacity and are not provided with plug-in outlets. The usual method of tapping off loads from feeder busways is by bus-bar connections or conduit and wire. The conduit and wire branch feeder connections are generally made through metal enclosures attached at the joint sections.

A layout of a typical feeder and plug-in busway system is shown in figure 12. In this figure a section of feeder busway extends from the transformer supply to the main protective device. From the protective device the feeder busway extends the full length of the plant to supply the individual plug-in busway branch runs. Because of the high-capacity requirements of feeder busways it is often necessary to arrange many bus bars in parallel and to interleave the phase conductors to obtain a low reactance. Such a feeder busway is shown by the photograph in figure 13. A multitude of arrangements may result in the application of feeder busways to and from

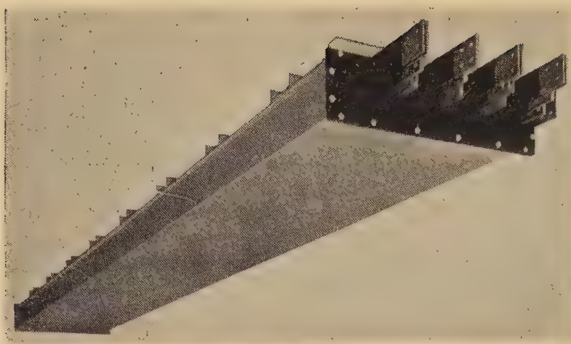


Figure 13 (left). Commercial design of interlaced feeder busway with steel backplate and ventilated aluminum enclosing channel

Figure 14. Example of feeder busway extending from a main distribution switchboard

switchboard, as is typified by figure 14.

Feeder busway systems, particularly for three-phase, four-wire light and power distribution, have been successfully used as risers in buildings having many floors. The load requirements of each floor are tapped off the busway and distributed through panel boards or plug-in busway.

A comprehensive treatment of the general problem of welding applications as reported by the AIEE subcommittee on power supply for welding applications,[16] is published in the May 1940 issue of Electrical Engineering. This activity has stimulated the development of feeder busways to provide designs for improved voltage regulation on welder service. These improved designs will be characterized by close phase-to-phase spacing of bus bars and convenient methods of extending conduit and wire feeders from the busway to welding machines.

Bibliography

1. Electricity and Magnetism, **Clerk Maxwell.** Volume II (1873).

2. Absolute Measurements in Electricity and Magnetism, **A. Gray.** Volume II (1893).

3. On the G.M.D. of Rectangular Areas and the Calculation of Self-Inductance, **E. B. Rosa.** Bulletin of the Bureau of Standards, volume 3, 1907.

4. Formulas and Tables for the Calculation of Mutual and Self-Inductance, **E. B. Rosa** and **F. W. Grover.** Bulletin of the Bureau of Standards, volume 8, 1912.

5. Experimental Researches on Skin Effect in Conductors, **A. E. Kennelly, F. A. Laws,** and **P. H. Pierce.** AIEE Transactions, volume 34, 1915, pages 1953–2018.

6. Skin Effect of a Return Circuit of Two Adjacent Strap Conductors, **H. B. Dwight.** *The Electric Journal*, April 1916, page 157.

7. The Reactance of Strap Conductors, **H. B. Dwight.** *Electrical Review and Western Electrician*, June 1917.

8. Skin Effect in Tubular and Flat Conductors, **H. B. Dwight.** AIEE Transactions, volume 37, 1918, pages 1379–1400.

9. Reactance Values for Rectangular Conductors, **H. B. Dwight.** *The Electric Journal*, volume 16, June 1919.

10. Untersuchungen uber Stromverdrangung in rechteckigen Querschnitten, **H. Schwenkhagen.** *Archiv für Electrotechnik*, volume 17, January 31, 1927, pages 537–89.

11. Current-Carrying Capacity of Busbars, **H. W. Papst.** *Electrical World*, September 21, 1929.

12. Calculation of Inductance and Current Distribution in Low-Voltage Connections to Electric Furnaces, **C. C. Levy.** AIEE Transactions, volume 51, 1932, page 903.

13. Engineering Calculation of Inductance and Reactance for Rectangular Bar Conductors, **O. R. Schurig.** *General Electric Review*, May 1933.

14. Reactance of Busbars. **H. B. Dwight** and **T. K. Wang.** AIEE Transactions, volume 57, 1938, pages 762–5.

15. Temperature Rise of Busbars, **H. B. Dwight, G. W. Andrew,** and **H. W. Tileston, Jr.** *General Electric Review*, May 1940.

16. Power Supply for Resistance-Welding Machines, **AIEE Subcommittee on Power Supply for Welding Operations.** AIEE Transactions, volume 59, 1940 (May section), pages 306–20.

Lead Storage Batteries in the Transportation Field

ROLAND WHITEHURST
MEMBER AIEE

Synopsis: A review of storage battery applications in the railroad, motor bus, and aircraft transportation fields. Historical notes are recorded of events in the development of gas and Diesel-electric rail cars and Diesel-electric locomotives, especially as those events relate to storage batteries. Similar treatment is given to other battery applications—car lighting, air conditioning, busses, and aircraft. The changes made in the construction of batteries for these services are described. Physical and electrical characteristics are emphasized where they have a bearing on the application.

Introduction

ELECTRIC starting of automobile engines is taken for granted until you have to crank one by hand. The drivers of 24,000,000 automobiles and 4,000,000 trucks which operate today, have little appreciation of the job done by storage batteries. Probably only those engineers intimately associated with the application of storage batteries in the transportation industry know of the degree to which storage batteries have performed much larger jobs. For example, they are used on all commercial air transports; they furnish the power to crank gas and Diesel engines on over 1,500 rail cars and locomotives, and on over 138,000 busses. Storage batteries also help to electrically air condition over 12,000 railway passenger cars, and they insure power supply to 40,000 signals used by the railroads for safe operation of trains. There are few who are familiar with the changes in design which were necessary to fit storage batteries to the peculiar requirements of certain transportation applications.

I. Railroads

A. Engine Cranking

1. *History.* At the beginning of the century a self-propelled rail car was introduced in which the electric driving motors received their power from a storage battery operating in parallel with a generator driven by a gasoline engine. The storage battery took care of peak loads and the generator furnished the average power required.

The forerunner of the present-day gas-electric rail car using variable voltage control appeared first in 1905. The engine was started by compressed air. About 1910, a small six-volt storage battery was added to furnish ignition current.

In 1905 a mechanically driven car known as the McKeen car was also introduced. Following Mr. Kettering's success of starting automobile engines by an electric motor in 1911, the idea was expanded to include the larger size gas engines then being applied to rail cars. Usually a 12-volt 120–160 ampere-hour storage battery served for cranking and lighting purposes.

There was a decided lull in the development of rail cars between 1912 and 1924. In the latter year an improved design of gas-electric rail car was introduced in which a 32-volt 215 ampere-hour storage battery was used for engine cranking, car lighting, and generator excitation. Thereafter a rapid expansion in the number of gas-electric rail cars took place. In Europe, on the other hand, gasoline was expensive and difficult to obtain, so that greater efforts were directed toward Diesel-powered rail cars.

In 1923 a Diesel locomotive, employing electric drive, was built in Europe. Starting windings were provided on the generator and the Diesel engine was cranked by the storage battery in this manner for the first time.

In February 1924 a 300-horsepower Diesel electric locomotive was placed in service in the United States. The engine was started by compressed air and a 16-cell 108 ampere-hour storage battery furnished current for excitation, control, and lighting. Two years later a 64-cell battery of the same capacity was added for engine cranking. Soon thereafter the cranking, excitation, control, and lighting circuits were connected to a common 56-cell battery.

In 1933 the Diesel-electric locomotive entered the high-speed passenger train field with a single 600-horsepower engine using a 64-volt 425 ampere-hour battery. Some of the present 6,000-horsepower locomotives are composed of three cab units operated by multiple-unit control. Each cab unit has two 1,000-horsepower engines and a 64-volt 425 ampere-hour battery.

In the early days of electric cranking of engines, it was the practice of locomotive manufacturers to use empirical formulas to determine the torques required to "breakover" and "fire" Diesel engines. By combining this information with the characteristics of the generator starting winding and a battery, it was possible to arrive at a suitable size of storage battery. Experience taught them that a battery sufficiently large to perform the cranking duty would adequately take care of the other electrical duties assigned to the battery. As engines grew larger it was desirable to re-examine the cranking requirements. Oscillograms were obtained of the starting conditions and the information used in a manner similar to that described in a paper delivered before AIEE at its 1940 summer convention in Swampscott, Mass.

2. *Adaptation of Storage Batteries.* Although the eight-hour battery capacity rating is traditional, it is of little value in Diesel cranking service, because, in this service, the battery must (1) "breakaway" the engine from standstill and (2) quickly bring it up to "firing" speed.

Condition (1) is essentially one of torque, and torque is proportional to amperes. The high breakaway torque has, in practice, required batteries to discharge at rates up to approximately their one-minute rate. To provide the necessary high-current rates, it is desirable to keep the internal resistance of the battery at a minimum and the current-carrying parts of adequate cross section. Condition (2) involves delivery of current for a reduced torque and at a voltage that will give speeds somewhat in excess of the minimum speed required for firing in order that the engine may fire quickly.

In order to satisfy both conditions, it has been found advisable to use multiple current-carrying posts, and to use copper inserts in these terminal posts and in the lead intercell connectors. Also cells were arranged in the trays in such a way as to make the intercell connectors as short as possible and the connectors were lead-burned to the terminal posts in order to reduce contact drop.

Figure 1 shows a typical characteristic of a battery used to crank a 900-horse-

Paper 41-34, recommended by the AIEE committee on land transportation, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted October 30, 1940; made available for preprinting December 9, 1940.

Roland Whitehurst is assistant general sales manager, The Electric Storage Battery Company, Philadelphia, Pa.

1. For all numbered references, see list at end of paper.

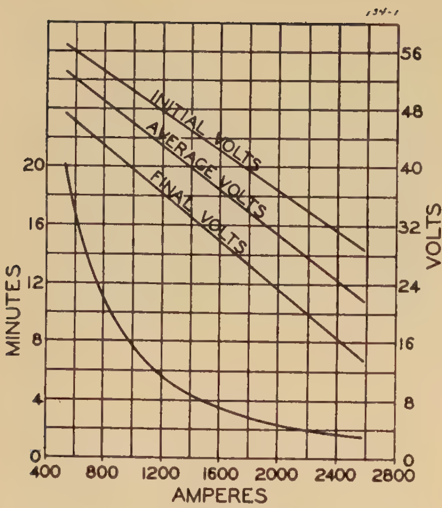


Figure 1. Discharge characteristic of a typical cranking battery

power Diesel engine. Figure 2 shows the accumulated horsepower of Diesel-electric locomotives in the United States.

B. Car Lighting and Air Conditioning

1. *History.* The first attempts at car lighting by electricity were made in 1881 and continued in an experimental stage for about ten years before practical results were obtained. The Planté type of storage battery which had been developed in 1860 was the first to meet car lighting requirements successfully. The Faure or pasted-plate type of battery was developed about 1881, but was not used in car lighting service until many years later because the earlier designs were not rugged enough. In the early types of car lighting batteries the elements were installed in alloy containers, two containers being grouped in a wooden tray. Porcelain rests supported the elements at a sufficient height from the bottom of the cell to provide space for sediment accumulation. Later, rubber jars were substituted for the alloy containers. In either case alloy or rubber covers were used.

Railroads operated well-equipped battery repair shops and regularly examined car lighting batteries, removing sediment, changing separators, and renewing plates when necessary. It was not uncommon to obtain a life of 20 years from negative plates, requiring three or four sets of positive plates. Gradually this practice of rebuilding batteries was discouraged by the railroads in favor of using a "single life" battery whose separators and plates would wear uniformly. The trend was definitely away from the Planté type and toward the lighter weight pasted-plate type battery.

In 1927 the first air-conditioned railway passenger car, a Pullman sleeping car, was placed in experimental service. Three years later the idea was tried by several railroads, and it was enthusiastically accepted by the traveling public. The rapid expansion of air conditioning on railroads in the United States is shown in figure 3.

Five different types of air-conditioning systems are used by the railroads. They are distinguished chiefly by the manner in which refrigeration is produced, and are separated as (1) ice activated, (2) mechanical compression with the compressor driven by an electric motor (electromechanical), (3) steam ejector, (4) mechanical compression with the compressor driven directly from car axle (direct mechanical), and (5) mechanical compression with the compressor driven by an internal combustion engine. The refrigeration capacities available for railway passenger cars vary from three to nine tons per 24 hours.

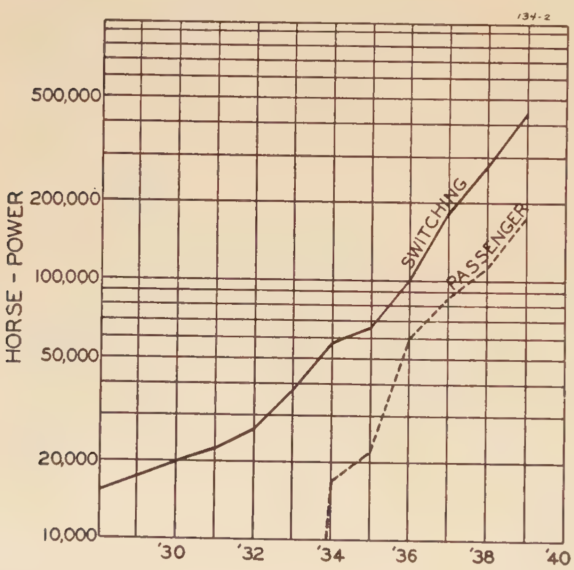


Figure 2. Cumulative horsepower of Diesel-electric locomotives in U.S.A.

Before describing the increased power requirements brought about by the addition of air conditioning, it will be helpful to refer to table I which shows what the Association of American Railroads set as a standard for storage battery and generator capacities when applied to *car lighting* service. The AAR is undertaking a study to make comparable recommendations for combined air conditioning and car lighting service. During the past three years better illumination has been emphasized and has been adopted in varying degrees by different railroads. Attractive interiors were provided on newly designed cars with new and improved types of lighting fixtures which meant further increases in intensity at the lighting source. In some of the latest cars the lighting load has reached a total of 170 amperes at 32 volts.

These heavier lighting loads plus any additional amount demanded by air-conditioning equipment are taken from the storage battery during periods of a train run when the train is operating below the cut-in speed of the generator and, in some cases, when the car is being precooled prior to a run. This was responsible for increasing the size of the storage battery to from two to four times that previously used in car lighting service alone. The capacity of generators was also increased to correspond with the increase in load. Experience indicates that a minimum generator capacity of 166 per cent of the connected load should be provided. While this ratio may seem somewhat high for new cars in long runs or express service, it is only a matter of time when such new cars are relegated to local or semilocal service in which higher generating capacity is desirable.

2. *Air-Conditioning Power Requirements.* The electric load in an ice activated system consists of 0.5 kw to the cooling coil fan and 0.75 kw to the cold water circulating pump or a total of approximately 38 amperes at 32 volts. In the majority of cases, one four-kilowatt axle-driven generator has sufficed. Referring to table II, it will be noted that the 600 ampere-hour size battery is the most popular. However, the lighting load and the type of car has influenced the choice of this capacity more than has the air-conditioning load.

The greatest range in power requirements occurs in the electromechanical system of air conditioning. Refrigeration capacities vary from 3.5 to 9.6 tons. In the vicinity of the six-ton rating, the total power requirements may vary from 8.5 kw to 12 kw. The motor driving the compressor requires approximately 93

per cent of this total, the remainder being consumed by evaporator fans, control, and in some cases, condenser fans. Comparisons made of various manufacturers' equipment rated around six tons showed that an average of 1.75 kw per ton of refrigeration was required, or a total of 10.5 kw at six tons. This represents an average increase above car lighting requirements of about 330 amperes at 32 volts. Generator capacities were raised to 15 kw, then to 20 kw, but it was not practical to increase the storage battery capacity correspondingly. Space and weight are limited and the problem became one of how much capacity could be installed in the standard AAR battery box. The electromechanical system of air conditioning imposed the greatest demands on the storage battery and there-

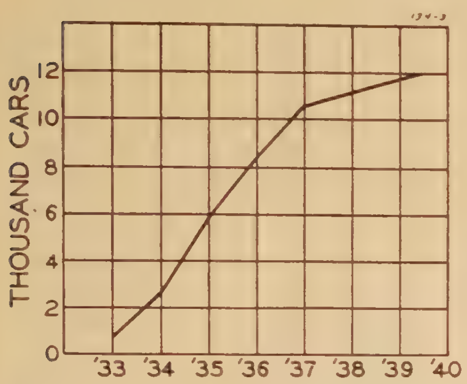


Figure 3. Air-conditioned railway passenger cars in U.S.A.

fore provided the greatest influence in the change of storage battery design. One of the large eastern railroads, a pioneer in the use of the electromechanical system, set 1,000 ampere-hours capacity (32 volts) of storage battery as a goal for manufacturers to strive to build and install within the standard compartment.

The power required in the steam ejector system is second to that of the electromechanical system. The total load amounts to approximately 104 amperes at 32 volts and consists of the condenser fan, condenser pump, cooling coil fan, and cold water pump. Referring to table II, it will be noted that the majority of installations use approximately 850 ampere-hour storage batteries. Generator capacities for this type of system vary from $7^1/_2$ kw to 10 kw, the latter size being found in most cases.

The direct mechanical system has the lowest electrical requirement and therefore the least effect on the size of battery installed. The 550 ampere-hour capacity was the most popular because one of the largest operators of air-conditioned cars chose it as their standard. It is estimated that the bulk of installations from 1938 to date used 600 ampere-hour batteries.

One manufacturer has developed an internal combustion engine which uses bottled propane for fuel and can be adapted to drive either a compressor or a generator. As an engine generator it removes the load from the car axle and there is no change in electric power used. When the engine is directly connected to the compressor, however, the electric power requirements drop to that of the direct mechanical system. Most of the installations of this type of system have been made on railroads in the Middle West and the preponderance of 450 ampere-hour storage batteries coincide with the standard size of car lighting battery of two large users.

3. Storage Battery Developments. The life of Faure or pasted plates depends on the cohesion of the active material and its retention by the grid structure. These are influenced by the porosity of the active material and by the shape of the grid section. Thus a soft porous plate will give higher capacity in its early life, but has a tendency to shed the active material. Hard dense plates do not give as much capacity initially, but are slower to "soften" with work and age, and consequently will give much longer life. It is of prime importance that plates be uniform because they will be "teamed" as groups in a battery which must work and wear evenly. To accomplish uniformity manufacturers must control closely not only the quality of materials used but also the physical conditions of manufacture, such as temperature, time and humidity, that exist while making and processing the plates.

A retainer or envelope is placed about the positive plate for a twofold purpose: (1) to hold the oxides in place mechanically and in contact with the grid, and (2) to delay oxidation of the separators. In one case the retainer has been a thin sheet of finely slotted rubber. In another case a modified Faure plate was made by enveloping a series of grid pencils with cylinders of active paste material and each cylinder encased in a finely slotted rubber tube. In a third case the retainer has been a thin mat of fibrous material usually made of spun glass.

Plate separators act as electrolytic diaphragms which permit current to pass freely between the plates but prevent any migration of dislodged active material from one plate to another of opposite polarity which might bridge and cause a short circuit. In some respects wood is an excellent material for separator use but its disadvantage lies in its inability to withstand high temperatures. In 1933 a new separator was developed from liquid latex, or the milk of rubber as the base. This material when compounded with certain other materials and vulcanized forms a microporous diaphragm which successfully withstands oxidation and heat. In another case a similar separator was obtained by vulcanizing a mixture of crude rubber and sulfur with certain other materials, the latter being dissolved out to form the minute pores.

The trays used for car lighting batteries were usually made from oak, maple, or long-leaf yellow pinewood, painted with an asphaltum paint and then immersed in a molten wax compound. Hard rubber jars held the elements and electrolyte, and the wood trays became the supporting structure for two or more jars. Such an assembly occupied more space and weighed more than a self-supporting container. Another disadvantage occurred when high temperatures melted the wax coating and exposed the wood to decay. A self-supporting rubber monobloc container was developed in 1935. This container saves space, is not subject to decay, and possesses a remarkable quality of toughness. It is handmade from rubber compounds which contain relatively high percentages of rubber. One type of container is made up of two dissimilar rubber compounds—one resistant to heat, the other resistant to shock—calendered together and handwrapped about mandrels, and then vulcanized. There are now over 50,000 of these monobloc containers in service.

Table I. AAR Recommended Battery and Generator Capacities for Railway Car Lighting

Class of Service	Amperes Load	Battery Capacity Range Ampere-Hours Min	Max	Generator Capacity (Kw)
Official, sleeping, parlor, mail, and dining cars having heavy lighting loads or severe operating conditions	50	350	600	4
Mail, dining cars, etc., where the lighting loads are not so heavy or the operating conditions so severe	35	300	350	3
Coaches, passenger-baggage cars, baggage cars under average operating conditions	25	200	300	2
Same cars as next above operating in slow speed branch line or local service	25	150	225	2

Table II. Storage Battery Installations in Air-Conditioning Service

Air-Conditioning System	Ampere-Hour Capacity Range		Electrical System (Volts)	Installations Made in 1933*	1934	1935	1936	1937	1938	Nine-Year Summary Total	Per Cent
Ice											
		300	110	0	0	0	3	3	0	6	0.2
	250	350	32	6	29	35	29	44	0	143	4.1
	375	450	32	25	50	314	360	31	1	781	22.5
		500	32	108	101	112	146	34	3	504	14.5
		600	32	97	538	511	594	165	13	1,918	55.1
	750	900	32	55	15	25	9	5	2	111	3.2
	1,000	1,200	32	6	2	0	0	4	0	12	0.4
Total				297	735	997	1,141	286	19	3,475	31
Compressor driven from an electric motor											
		300	110	0	7	30	47	26	5	115	5.4
		450	64	0	11	7	0	0	0	18	0.8
		500	64	0	0	60	50	75	50	235	11.1
		600	64	0	6	57	62	104	8	237	11.2
	750	800	32	10	33	20	16	0	0	79	3.8
	900	1,000	32	188	292	486	174	282	3	1,425	67.2
	1,200	1,250	32	0	0	4	0	0	2	6	0.2
		2,000	32	3	3	0	1	0	0	7	0.3
Total				201	352	664	350	487	68	2,122	19
Steam ejector											
	550	600	32	2	20	57	78	31	109	297	15.6
	700	800	32	3	37	35	72	40	6	193	10.2
	850	875	32	0	132	407	145	327	152	1,163	61.2
	900	950	32	33	2	10	12	72	1	130	6.8
		1,000	32	5	6	28	14	35	20	108	5.7
		1,200	32	0	0	0	0	10	0	10	0.5
Total				43	197	537	321	515	288	1,901	17
Compressor driven mechanically from car axle											
	300	350	32	0	6	118	9	30	4	167	5.0
	375	450	32	33	74	17	74	88	0	286	8.5
		450	64	0	4	0	0	0	0	4	0.1
		500	32	12	19	61	30	75	0	197	5.9
		550	32	0	395	882	505	363	54	2,199	65.9
		600	32	61	1	4	14	91	62	233	6.9
		600	64	0	32	0	0	0	0	32	1.0
	800	900	32	0	0	21	3	63	63	150	4.5
		1,000	32	0	62	2	0	3	0	67	2.1
		1,250	32	0	0	0	0	0	2	2	0.1
		1,800	32	0	0	1	0	0	0	1	
Total				106	593	1,106	635	713	185	3,338	30
Compressor driven from internal combustion engine											
	200	400	32	0	0	1	1	36	11	49	15.4
	450	600	32	1	0	3	57	146	29	236	74.3
	750	850	32	0	1	13	0	8	0	22	6.9
	900	1,000	32	0	0	1	3	6	1	11	3.4
Total				1	1	18	61	196	41	318	3
Grand total				648	1,878	3,322	2,508	2,197	601	11,154	100

*This also includes all installations made prior to 1933.

In order to minimize IR drop, number 0000 cable composed of upward of 5,000 strands of wire is used to connect adjacent battery trays where 800 to 1,000 ampere-hour batteries are used. Extra flexible cable is required for the larger batteries which practically fill available compartment space. One alternative for reducing the large cable requirement has been adopted by several railroads when the system voltage was doubled to 64- and 32-cell 500 ampere-hour or 600 ampere-hour storage batteries used. In another case one railroad equipped 115 cars with 110-volt lighting and air-conditioning systems.

Table III compares a 300 ampere-hour Planté car lighting battery of 1920 with a typical car lighting battery as used today. Today the railroad can obtain a 300 ampere-hour car lighting battery that will occupy one-third the volume of the 300 ampere-hour Planté battery used in 1920; it will weigh only 40 per cent of the 1920 battery; it will cost only 70 per cent as much, and will have a longer life expectancy.

For heavy duty air-conditioning service, it is now possible to install a 16-cell 1,000 ampere-hour battery in the same size compartment which formerly held 16 cells of a 400 to 450 ampere-hour battery. The increased cycling of the battery together with the heavier loads mean higher operating temperatures which are now permissible because of the present development of plate separators. Tightly packed elements permit today's storage batteries to operate throughout their life without mechanical failure of the separators which otherwise might be caused by vibration. Compared with the 1920 300 ampere-hour car lighting battery, the railroad can obtain today an air-conditioning battery of $3^1/_3$ times the capacity installed in the same size compartment, weighing only 25 per cent more, costing only 70 per cent more, and, when used on a load ten times greater, having a life expectancy equal to the 1920 battery.

C. Street Railway PCC Cars

Several papers have been presented to the Institute on "Presidents Conference Committee" street railway cars. Today there are about 1,500 of these PCC cars in service in this country, each of which is equipped with a 16-cell 55 ampere-hour storage battery. The battery is connected across a voltage-regulated motor-generator set. The loads on the battery circuit include magnetic track brakes, control, step treadle equipment, headlight, stop lights, marker lights, passenger signal system, instrument panel, and sometimes fare box lighting. The total load may reach a maximum of 75 to 80 amperes while magnetic track brakes are energized.

II. Motor Busses

Passenger busses are classified along with passenger automobiles and trucks as automotive equipment. While technical discussions on this subject are nor-

mally conducted by SAE, a few remarks on the application of storage batteries to busses may be appropriate in view of their widespread use for commercial transportation.

The year 1911 marked an important milestone in the development of automotive equipment, for it was in that year the electric starting motor for gasoline engines was introduced. Prior to that time all automotive engines were cranked by hand. A campaign for better illumination of bus interiors brought greater lighting loads and in order to minimize voltage drop, a 12-volt circuit was standardized. Battery sizes increased with the change in lighting load from 13 plates to 17 plates and in some cases up to 25 plates. Bus battery plates were thicker than those used in automobile batteries because busses operated in more continuous service and under more adverse conditions.

In railway, marine, and stationary battery applications it is customary to rate the batteries on an eight-hour basis, whereas in bus service it is customary to rate them on the four-hour basis. The capacity of bus batteries was at one time selected on the basis of a six-hour reserve for the operating load exclusive of the starting motor. From experience it was found that a size capable of supplying this reserve was ample for any starting conditions normally encountered. Today the electric loads on busses reach values of 65 amperes at 12 volts and the size of battery recommended is one that will carry the load for four hours.

Fuel economies associated with Diesel engine operation helped to bring about the development of the small high-speed Diesel for bus and truck service. Two six-cell bus-type batteries are connected in series for 24-volt starting and then paralleled for 12-volt lighting.

In 1935, trolley busses made their appearance with 12-volt storage batteries used for control and lighting purposes to avoid high trolley voltages within the bus.

III. Aircraft

Military planes have been responsible for most developments of aircraft electric equipment. The Liberty motor in service during World War I was the first to use a storage battery for ignition. The battery weighed 11 pounds and contained four cells with seven plates per cell.

By the end of that war, military planes were being equipped with direct drive starters. The cranking batteries were usually six-cell, 20, 35, or 70 ampere-hours capacity (five-hour rating). Similar equipment was used by mail and commercial planes about 1925.

The inertia starter, brought out in 1925 plus an improved design of generator, hastened the adoption of electric starting of aircraft engines. Because of the importance of weight, very thin pasted-plate batteries were developed for aircraft service. The plates used in the first Army plane batteries were only 0.05 inch thick. As airplane flights became longer, swifter, and more severe on auxiliary equipment, it was found desirable in 1930 to increase the plate thickness by 50 per cent.

Table III. Comparison of 1920 and 1940 Typical Car Lighting Batteries

	1920	1940
8-hour capacity	300 A.H.	300 A.H.
No. cells per tray	2	4
Tray material	Wood	Rubber monobloc
Tray dimensions		
Length	$24^3/_4''$	19
Width	$11''$	$9^3/_4''$
Height	$19^1/_4''$	$19^3/_4''$
No. trays per battery	8	4
Total battery volume	24.26 cu. ft.	8.5 cu. ft.
Total battery weight	2,600 pounds	1,010 pounds
Purchase price	100%	70%
Expected life	5 years	7 years

It is interesting to note that a modern passenger airplane's intermittent load on a 12-volt circuit may total 225 amperes. During a $5^3/_4$-hour night flight in the winter, a typical example of the electric load would be about 490 ampere-hours at 12 volts normally supplied by two 50-ampere generators in parallel. The six-cell 13-plate battery used in this example weighs 78 pounds, has a capacity of 88 ampere-hours (five-hour), and occupies a space 14 by 7 by 11 inches high. It would be capable of carrying 150 amperes for 18 minutes or 200 amperes for 12 minutes.

The large 21-passenger skyliners have two 850-horsepower engines, two storage batteries like the one described above, and means to use either battery or both connected in parallel. The latest Stratoliners have four 1,150-horsepower engines and two 24-volt 50 ampere-hour batteries. The very large engines are using the direct drive starter again rather than the inertia starter. To conserve battery capacity, the heavy duty cranking prior to a plane's departure from an airport, is taken care of by a portable ground-cranking battery which is wheeled under the plane.

Future Developments

Thought and study is being devoted to heating railway passenger cars electrically. Air conditioning includes the proper control of temperature and humidity of the air during winter months as well as summer months. At least three manufacturers are now developing engine-driven equipment that will heat, light, and air condition a car. On one system it is planned to generate 220 volts three-phase, alternating current for heating and air-conditioning purposes. A 64-volt 150 ampere-hour battery will be used to crank the engine, provide the control circuit energy, and light the car. The battery will be charged from the exciter. The adoption of 64 volts direct current for lighting permits the use of a recent development—the fluorescent tube which operates at 60 volts direct current from the battery circuit without transformation of energy. Thus the engine may be shut down temporarily without affecting the source of illuminating power.

In view of the large quantities of rubber materials now used in the production of lead storage batteries, some concern is felt for the continuity of crude rubber supplies. While numerous synthetic rubber substitutes are now being marketed, little enthusiasm can be expressed for any one of them at this time, because experience has taught us to be wary of any possible unhappy union of storage battery electrolyte with an element from the synthetic material. Research is now directed toward the use of some of the newly developed plastics, and it is predicted that they will find increased use in the storage battery industry.

References

1. The Gas Electric Car—Characteristics and Operating Features, L. C. Josephs, Jr. *Proceedings* of Association of Railway Electrical Engineers, October 1931, page 237.

2. Self-Propelled Railway Passenger Cars, S. T. Dodd. *General Electric Review*, 1913, page 637.

3. Engineering Report on Air Conditioning of Railroad Passenger Cars, prepared by Division of Equipment Research, Association of American Railroads, April 15, 1937.

4. Statistics on Generator and Storage Battery Capacities Used on Air Conditioned Cars obtained from the following issues of *Railway Electrical Engineer:* February 1934; December 1934; March 1936; February 1937; February 1938; April 1939.

5. Investigation of Starting Requirements of a 660 Horsepower Locomotive Diesel Engine, J. C. Davidson and R. Lamborn. AIEE Transactions, volume 60, 1941 (January section), pages 31–4.

Bushing and Associated Insulation Testing by the Power-Factor Method

C. C. BALTZLY
MEMBER AIEE

E. L. SCHLOTTERE
NONMEMBER AIEE

I. Introduction

THE periodic cleaning, inspection, and testing of equipment plays a very important part in obtaining service continuity. The cost of the labor and equipment involved in locating and eliminating defective apparatus by the above procedure may well be charged to that hypothetical account known as "preventive maintenance." The economics of the procedure, however, must be governed by the results obtained.

For many years, bushings and associated insulation such as the internal parts of circuit breakers and windings of instrument and power transformers were tested by methods which were frequently unreliable, inadequate or of a destructive nature. During the past ten years the a-c test known as the power-factor method of insulation testing has gradually been replacing the former methods used for periodic checkup. It is also gaining recognition as one of the requirements in the acceptance tests made on certain types of new equipment.

The results obtained by Philadelphia Electric Company, using the power-factor test method for approximately eight years, has warranted the continuation of a periodic test program. A few bushing failures still occur but they are confined mostly to the low-impulse type of design and cannot be anticipated by any nondestructive type of test. A centralized bushing repair shop has provided the means for salvaging bushings and other equipment at a reasonable cost, for years of useful life. All equipment rejected by test has, upon investigation, disclosed faulty insulation which warranted its removal from service.

II. Scope of Testing

The power-factor method of insulation testing was first used by this company in 1933, and was confined primarily to outdoor oil circuit breaker bushings. The Doble type *I* tester was used for this work and the results of the first three years' work has been previously summarized.[1]

In 1936, a second type *I* tester was placed in service and the range of testing was broadened to include power and instrument transformers and lightning arresters. With the further development of test equipment by the Doble Company, the two type *I* sets were replaced in 1939, by an *I*-10 and an *I*-30-150 set. A type *U* set was also obtained for use in the bushing repair shop in 1938.

The power-factor testing outlined for each year is as follows:

(*a*). Outdoor oil circuit breakers.

(*b*). Power transformers.

(*c*). Instrument transformers, alternated every other year with station-type lightning arresters.

(*d*). Cold collar and/or hot collar tests on all bushings containing a compound filler.

(*e*). Hot-guard test on all draw-lead type transformer bushings.

(*f*). Oil samples on all power transformers.

(*g*). Oil samples on all oil circuit breakers and instrument transformers as necessitated by over-all test results.

(*h*). Spare bushings.

(*i*). Follow-up field tests as required.

(*j*). Indoor oil circuit breakers during winter months.

(*k*). Follow-up and acceptance tests on all equipment reconditioned in the shop (by the shop force).

(*l*). Acceptance tests on all new bushings.

(*m*). Base checks on all new power transformers.

III. Field Testing

The technique of field testing has been very thoroughly covered in previously published articles,[2–7] listed in the bibliography and will, therefore, not be repeated.

It requires about two years' work to completely cover the outdoor equipment on the Philadelphia Electric Company system. However, the most important locations are tested yearly. A tentative schedule allocating the work is made up each year as a guide for the field test men. Due to its larger capacity, the *I*-30-150 set is used for practically all power transformer tests.

In order to insure proper follow-up of rejected equipment, a 3- by 5-inch card is used for each piece of equipment tested (bushings are included with the circuit breaker) and the condition of the equipment is noted as satisfactory, follow-up, or rejected. These cards are sent daily to the superintendent in charge of the location where the testing is being done. A summary sheet of all rejected equipment is made up weekly and forwarded to the general superintendent of the respective division. When the testing at a specific location has been completed, a copy of each data sheet, approved by the supervisor in charge of the tests, is forwarded to the superintendent of that location for reference and file.

Field testing is seldom carried on when the ambient temperature is lower than five degrees centigrade or when the humidity is high enough to cause considerable surface leakage. The rating schedule for bushings and instrument transformers at 20 degrees centigrade ambient temperature is given in table I.

An arbitrary value of five per cent maximum at 40 degrees centigrade has been established for power transformers although it is still a moot question as to the satisfactory condition of the winding insulation when lower than one per cent especially when subjected to a dry-out run. The current and watts loss readings must also be carefully analyzed and due consideration given to the type of insulation and winding construction before the unit is accepted or rejected.

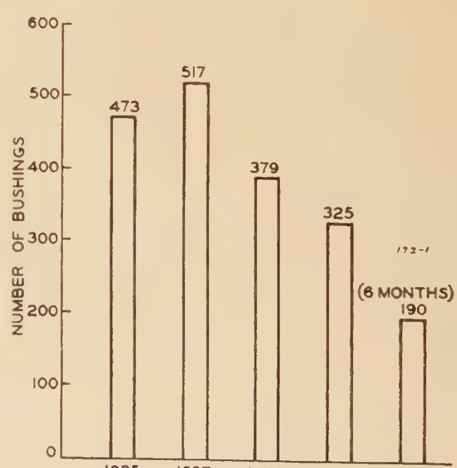


Figure 1. Bushings reconditioned in the shop. Total for 5 ½ years = 1,884

Paper 41-72, recommended by the AIEE committee on standards, and presented at the AIEE winter convention, Philadelphia, Pa., January 27–31, 1941. Manuscript submitted November 22, 1940; made available for preprinting December 21, 1940.

C. C. BALTZLY is general superintendent, station operations, Philadelphia Electric Company, Philadelphia, Pa. Mr. SCHLOTTERE is also with this company.

1. For all numbered references, see list at end of paper.

Considerable work has been done since 1937, in the investigation of station-type lightning arresters such as the oxide film, type *BO;* auto-valve, type *SV* (disk and porous block construction); and Thyrite, types *LAIB* and *LAIY.* Arbitrary values obtained by comparison and internal investigation of units are being used rather successfully but it is hoped that compilation of further data will offer a more direct solution of the problem.

Wood members, insulators, and the porcelain-tube type of wall bushings are analyzed on the basis of current and watts loss data rather than by power factor. Satisfactory oil is found to be one per cent or under. Above that value other tests, such as dielectric, acidity, color, etc., are made before rejection.

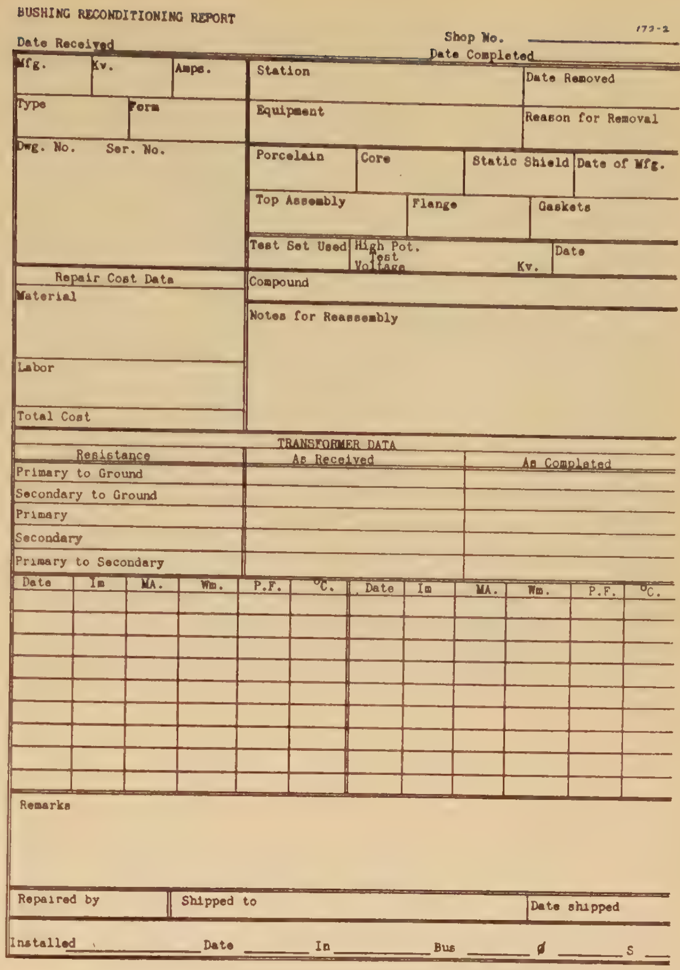
IV. Test Results

A. Bushings (Field Test)

For the three-year period 1933–35 inclusive, about 6,000 bushings were tested. Since that time approximately 4,000 bushings are tested in the field each year. Table II indicates that 1,493 bushings of various types and voltages have been rejected in the past five years. This represents about 7.5 per cent of the total number tested. It should be noted that the rejection of indoor bushings during the past four years accounts for approximately 30 per cent of the total number rejected. The rating schedule was arbitrarily lowered for the indoor bushings on the basis that they would only be tested at four- or five-year intervals.

Table III presents a breakdown of the reasons for rejection. Power factor accounts for 65 per cent of the total and compares with the results of the 1933–35 period[1] of 63.8 per cent. However, in order to make a fair comparison, the indoor bushings must be deducted which would then approximate 35 per cent instead of 65 per cent. This indicates that the trend is downward which should be expected in order to justify the expenditures made in replacement and reconditioning. Moisture accounts for more than 90 per cent of the rejections by power factor.

The 17 per cent rejection due to oil migration and compound leaks is confined largely to transformer bushings and is usually determined by inspection rather than test. The "miscellaneous rejections" is somewhat high (14 per cent) due to placing a number of multipiece porcelain bushings which were rebuilt with single-piece porcelain, in this classification. The percentage of miscellaneous rejections would be in the order of three per cent or less if this modernization item were omitted.


BUSHING RECONDITIONING REPORT

172-2

Date Received

Shop No.

Date Completed

Mfg. | Kv. | Amps. | Station | Date Removed

Type | Form | Equipment | Reason for Removal

Dwg. No. Ser. No. | Porcelain | Core | Static Shield | Date of Mfg.

Top Assembly | Flange | Gaskets

Test Set Used | High Pot. Test Voltage Kv. | Date

Repair Cost Data

Material | Compound

Notes for Reassembly

Labor

Total Cost

TRANSFORMER DATA

Resistance | As Received | As Completed

Primary to Ground

Secondary to Ground

Primary

Secondary

Primary to Secondary

Date | Im | MA. | Wm. | P.F. | °C. | Date | Im | MA. | Wm. | P.F. | °C.

Remarks

Repaired by | Shipped to | Date shipped

Installed Date In Bus ∅ S

Figure 2. Bushing reconditioning report

B. Bushings (Shop Test)

The bushing reconditioning shop was started in 1935. Figure 1 shows the number of bushings reconditioned since that time. The total of 1,884 consists of all types of bushings ranging from 7.5 kv to 73 kv. The first year was devoted to the training of personnel, experimentation with materials and methods, building special racks, providing special tools, etc. Larger ovens were designed and installed in 1936, so that large-scale production did not get under way until 1937. During the period 1935–37, it was necessary to assign a field man for shop testing several days each week. This decreased the amount of outdoor testing possible and at the same time proved to be inadequate to meet shop requirements. In 1938, a Doble type *U* set was provided. The shop men now average about 3,000 tests (follow-up, acceptance, etc.) per year.

All bushings (15 kv to 73 kv) after being reconditioned are subjected to a one-minute hold voltage test using the values recommended by the manufacturer for present-day design. This test has resulted in the elimination of a few older type bushings which probably would have failed in service due to faults which could not be determined by a nondestructive test.

Figure 2 is the form developed for detailing the shop history of bushings and instrument transformers. Figures 3 and 4 show the front and rear view of the type *U* tester used in the shop.

C. Transformers

During the past four years, 493 power transformers have been tested. This group of transformers covered a voltage range from 13.2/2.3 kv to 220/66/13.2 kv and a capacity range of 100 kva to 43,333 kva single phase and 1,000 kva to 20,000 kva three phase. All low-voltage windings (2.3 kv and 4 kv) are tested at 5 kv, the higher voltage windings at 10 kv. From the test data obtained, the transformers have been divided into three groups as follows:

Per cent power factor at 40 degrees centigrade: under 5.0, 274; 5.1 to 10.0, 136; over 10, 83.

This grouping is used as a follow-up in

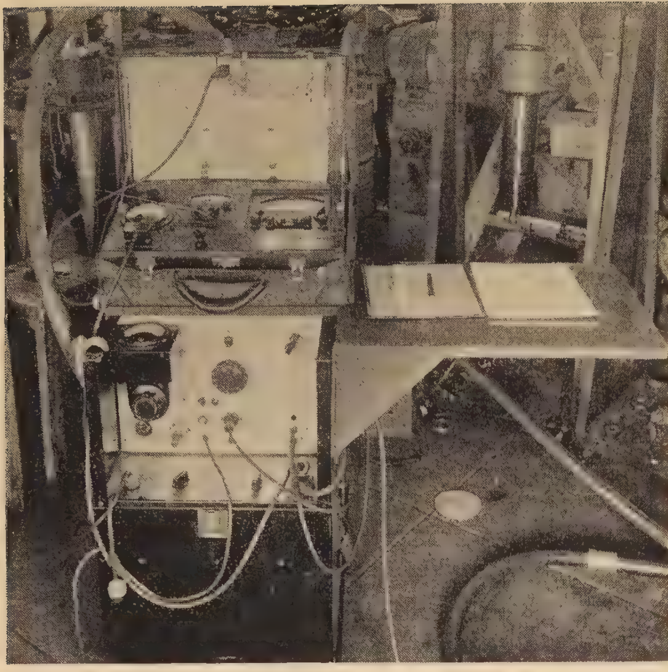


Figure 3. Front view of type U tester used in reconditioning shop

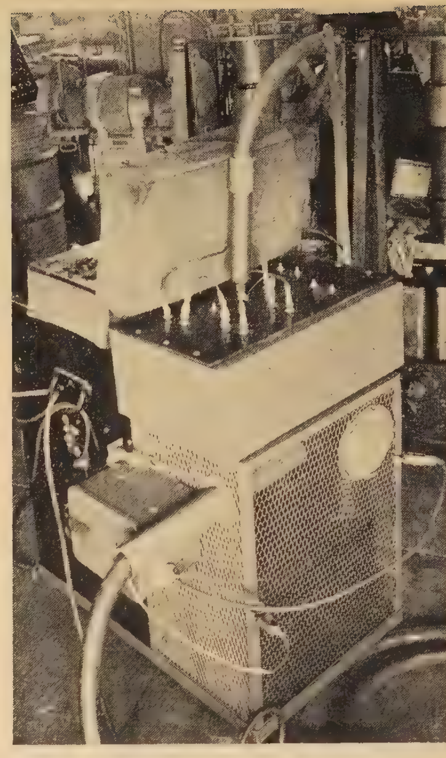


Figure 4. Rear view of type U tester used in reconditioning shop

order to determine the trend of deterioration in the various units of a group from year to year.

Table IV shows the results obtained in drying out seven units in 1937. In all cases, the windings were removed from the tanks and dried out by the hot air method at 85 degrees centigrade. Subsequent tests to date on these transformers have shown that the "as left" readings have remained stabilized. The bushings were reconditioned in the shop and are included in both the "as found" and "as left" readings. Moisture was the contributing factor to the high pow in each case.

Instrument transformers and metering units rejected during the past five years are listed in table V. These units were reconditioned in the shop and again moisture was found to be the major cause for rejection.

D. Miscellaneous

Several hundred defective supporting insulators have been removed from service either as a direct result of being found by test or by the inspection of equipment by the field test man.

Wood cross braces, *A* frames, lift rods, etc., have been reconditioned due to field investigation and rejection.

Power-factor test on oil samples is used as one of the criteria for recommending reconditioning.

Testing of lightning arrester units by power factor has resulted in the reconditioning of several hundred units due to

Table I A. Bushing Power-Factor Rating Schedule

Bushing Condition	Per Cent Power-Factor Limits for Various Type Bushings at 20 Degrees Centigrade				
	Kv	Condenser	Oil-Filled	Compound	Porcelain*
Satisfactory	15-37	0–3.0	0–3.5	0 3.5	0–3.5
Satisfactory	73–230	0–2.0	0-2.0	0-2.5	0–3.5
Follow-up	15-37	3.0–5.0	3.5–5.0	3.5 5.0	3.5–6.0
Follow-up	73–230	2.0–3.0	2.0-3.0	2.5–4.0	3.5–5.0
Replace	15–37	Over 5.0	Over 5.0	Over 5.0	Over 6.0
Replace	73-230	Over 3.0	Over 3.0	Over 4.0	Over 5.0

* Current and watts readings are of more value than power factor for this type of bushing.

Application of the above values may be somewhat arbitrary based on type of bushing construction, service requirements, and analysis experience. Approximately eight years of use has proved their reliability.

Table I B. Instrument Transformer Power-Factor Rating Schedule

Type P.T.	Per Cent Power-Factor Limits at 20 Degrees Centigrade			Type C.T.	Per Cent Power-Factor Limits at 20 Degrees Centigrade		
	Satisfactory	Follow-Up	Replace		Satisfactory	Follow-Up	Replace
E-15	5.0	5.0–7.0	Over 7.0	*K*-31	3.0	3.0–5.0	Over 5.0
E-115	5.0	5.0–7.0	Over 7.0	*K*-32	4.0	4.0–6.0	Over 6.0
E-16	3.5	3.5–5.0	Over 5.0	*K*-61	3.0	3.0–5.0	Over 5.0
E-116	3.5	3.5–5.0	Over 5.0	*K*-204	2.5	2.5–4.0	Over 4.0
P	3.5	3.5–5.0	Over 5.0	*OA*	4.0	4.0–6.0	Over 6.0
(34.5 kv) *VC*	3.5	3.5–5.0	Over 5.0	*O*-37	3.0	3.0–5.0	Over 5.0
(73 kv) *VC*	2.5	2.5–4.0	Over 4.0	*KE* (meter unit)	2.5	2.5–4.0	Over 4.0

broken castings, defective seals, corroded internal parts, etc.

V. Bushing Failures

Moisture was responsible for 69 per cent of the 48 bushing failures occurring between 1932 and 1940, as shown in figure 5. Entrance to the bushing was gained in most cases through defective gaskets or cement seals. In 1935, 12 of the 15 failures were caused by defective gaskets. This led to the program of replacing the top gaskets on nearly 1,000 bushings in place as previously reported.[1] Of the total failures (48), 27 per cent had never been tested and 6 per cent had been recommended for replacement previous to failure. The type *SI* compound-filled bushing was involved in 69 per cent of the failures with the condenser type accounting for 23 per cent. While it is not expected that failures will be eliminated entirely, it is definitely realized from the experience gained during the past eight years that many incipient failures were removed from the system.

Very few follow-up tests are made since the reconditioning shop was established. A bushing is now recommended for reconditioning if it does not pass the "satisfactory" rating. This eliminates the possibility of a failure between tests because the rate of deterioration is an unknown factor and also provides more time for productive effort on that equipment yet to be tested.

VI. Conclusions

From the experience gained and the data compiled in eight years of testing and reconditioning, the following conclusions may be logically presented.

1. The power-factor test has provided an adequate nondestructive method for determining insulation deterioration.

2. It is satisfactory in the results obtained and therefore justifies its continuation.

3. Due to the unknown factor "rate of deterioration" the period for testing of equipment at important locations should not exceed one year.

4. The major factor in insulation deterioration is moisture.

5. The rating schedules used for various types of equipment have proved satis-

Table II. Number of Bushings Rejected (1936 to 1940)

		Condenser	Oil-Filled	(SI) Compound	Porcelain	Total
1936	O.C.B.	119*	1	130	4	254
	trans.	38†	6	142	24†	210
1937	O.C.B. (outdoor)	35	33**	32	7	107
	O.C.B. (indoor)	32			1	33
	trans.	3		70	4	77
1938	O.C.B. (outdoor)	52		108	1	161
	O.C.B. (indoor)	252				252
	trans	2		39	32	73
1939	O.C.B. (outdoor)	10	2	24		36
	O.C.B. (indoor)	156		5		161
	trans.	1	1	26	7	35
1940 (partial)	O.C.B.	8	2	57		67
	trans.	7		12	8	27
Total		715	45	645	88	1,493
Per cent of total rejected		48	3	43	6	

*Includes a change from multipiece to single-piece porcelain.

**Includes a rebuild of 24 obsolete type bushings.

†Includes 10 condenser and 18 porcelain bushings damaged by fire.

Table III. Reasons for Rejection (1936 to 1940)

		Power Factor	Oil Migration and Compound Leaks	Broken Porcelain	Miscellaneous*	Total
1936		286	86	43	49	464
1937	outdoor	113	55	9	7	184
	indoor	32		1		33
1938	outdoor	79	53	3	99	234
	indoor	252				252
1939	outdoor	26	22	2	21	71
	indoor	156	5			161
1940 (partial)		25	34	4	31	94
Total		969	255	62	207	1,493
Per cent of total rejected		65	17	4	14	

*Includes voids, low compound level, defective cement and litharge seals, defective gaskets, carbonized compound, certain modernization, etc.

Table IV. Results Obtained in Drying Out Seven Power Transformers, Oil Conservator Type

Case Number		Kva	Voltage	Phase	Oil: Temperature Degrees Centigrade	Oil: Power Factor	Winding Power Factor at 40 Degrees Centigrade: High+Low	High	Low
1	as found	333	13.2/4	1	0	0.2	46.8	20.8	40.5
	as left				15	New	2.94	2.07	3.98
2	as found	5,000	33/4	3	12	1.7	23.4	5.2	24.3
	as left					New	3.44	1.14	2.46
3	as found	3,333	33/13.2	1	30	0.8	30.6	12.4	23.4
	as left				27	New	3.3	0.7	2.8
4	as found	3,333	33/13.2	1	30	0.9	34.3	12.5	26.8
	as left				27	New	2.8	0+	3.1
5	as found	833	13.2/2.3	1	25	10.9	36.4	32.3	27.1
	as left				30	New	5.7	2.5	3.5
6	as found	833	13.2/2.3	1	25	11.3	39.4	33.0	30.1
	as left				30	New	4.9	1.75	3.7
7	as found	833	13.2/2.3	1	25	4.6	9.0	13.4	8.8
	as left				30	New	5.2	3.5	3.6

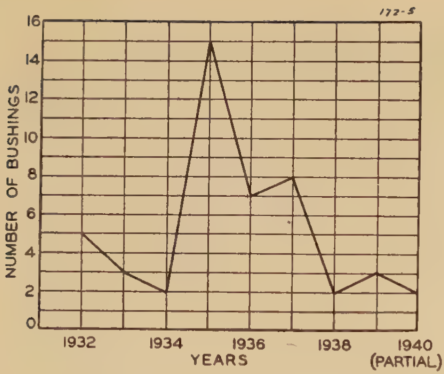


Figure 5. Bushing failures

Cause:
Moisture.................69 per cent
External..................23 per cent
Impulse.................. 6 per cent
Internal pressure.......... 2 per cent

factory in that the investigation of all rejected equipment has disclosed faults warranting its removal from service.

6. A close inspection should be made of all seals on bushings namely, gaskets, cement, litharge, etc., for defective seals have accounted for the largest number of failures.

7. Faulty equipment should be removed from service immediately and in extreme cases, equipment held out of service until such replacement is made.

8. Reconditioning of equipment may be accomplished at a reasonable cost and at the same time provide years of useful life to equipment that might otherwise prove to be a costly emergency repair job.

9. A centralized shop, where reconditioning is being done by the power company, provides the most economic and reliable method of reconditioning insulation.

Table V. Instrument Transformers Rejected by Power Factor (1936 to 1940)

	Type P.T.	Number Rejected	Type C.T.	Number Rejected
1936	*VC*	17	*OA*	2
	P	6	*K*-32	5
	E-15	4	*K*-61	2
	E-116	8	*K*-204	1
			KE (meter unit)	2
	Total	35		12
1937	*VC*	9	*K*-32	2
	P	2		
	E-15	2		
	E-16	16		
	E-116	10		
	Total	39		2
1938	*VC*	6	*K*-204	1
	E-115	2		
	E-116	1		
	Total	9		1
1939	*E*-15	2	*K*-32	1
1940 (partial)	*VC*	2	*K*-204	1
	E-116	13		
	Total	15		1

10. Reconditioned equipment in service is showing no increase in power factor in subsequent field tests.

11. The experience gained has provided the means for a more logical consideration of new design.

12. The economics involved in this type of testing cannot be evaluated, but from the standpoint of "preventive maintenance," service continuity, and customer satisfaction, it is unquestionably justified.

Bibliography

1. Bushing P.F. Tests Show Failure Causes, **E. L. Schlottere.** *Electrical World*, March 28, 1936, pages 34–7.

2. Testing Bushings and Insulation by Power Factor Method, **I. W. Gross** and **H. E. Turner.** *Electrical World*, January 13, 1934, pages 68–73, and January 20, 1934, pages 111–16.

3. Portable Schering Bridge for Field Tests, **C. F. Hill, T. R. Watts,** and **G. A. Burr.** AIEE Transactions, volume 53, 1934 (January section), pages 176–82.

4. Discussions of above paper—AIEE Transactions, volume 53, 1934 (April section), pages 618–22.

5. Field Testing of Bushings and Transformer Insulation, **I. W. Gross.** AIEE Transactions, volume 57, 1938 (October section), pages 589–96.

6. Power Factor Testing of Transformer Insulation, **Frank C. Doble** and **G. H. Browning.** *Electrical World*, December 2, 1939, pages 49–50.

7. High Voltage Bushings Tested in Place, **C. F. Benham.** *Electrical World*, September 28, 1935, pages 29–30. 77.

What Insulator Strength Is Your Guide?

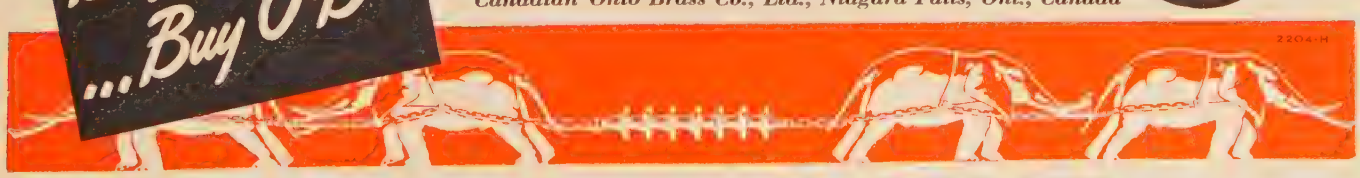
Several mechanical strength values can be determined for a group of suspension insulators—actual and probable maximums, averages and minimums, and various time-loads. But only one type of these values—MINIMUM STRENGTH—can be used as a reliable guide in selecting insulators because the weakest unit establishes the strength of an entire insulator string. This basic principle explains why so many transmission engineers are using minimums. And it reveals the vital portent of the fact that *M & E ratings of all O-B suspension insulators are now their minimum strengths.* Providing designers with dependable insulator minimum values is one important advantage of the greater strength of O-B's suspensions. Another significant benefit is that lower-rated, *lower-priced* insulators can be used for many installations since O-B recommends 50 per cent of the minimum M & E rating as the safe working load. To get these extra strong suspension insulators, noted for long life and having reliable minimum strengths equal to or greater than their M & E values—buy O-B!

Buy the Best ...Buy O-B

Ohio Brass

MANSFIELD, OHIO, U. S. A.

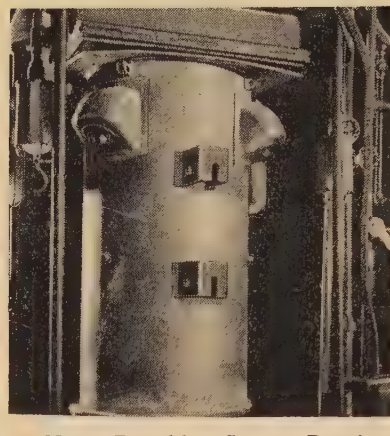
Canadian Ohio Brass Co., Ltd., Niagara Falls, Ont., Canada



ELECTRICAL ENGINEERING. Published monthly by the American Institute of Electrical Engineers; publication office 20th & Northampton Streets, Easton, Pa. Editorial and advertising offices, 33 West 39th Street, New York, N. Y. Subscription $12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain and Spanish colonies; $13 to Canada; $14 elsewhere; single copy $1.50. Entered as second-class matter at the Post Office, Easton, Pa., under the Act of Congress of March 3, 1879. Accepted for mailing at special postage rates provided for in Section 538, P L. & R. Act of February 28 1925. June 1941, Vol. 60, No. 6. Number of copies this issue 22,800.

REASONS WHY ENGINEERS CHOOSE THE NEW

1 Simplified Supports for Direct Pole Mounting Cut Installation Time. Standard Support Spacing and Bushing Location Mean Complete Interchangeability of All Sizes and Makes.



2 New, Durable, Copper-Bearing Steel Tanks. Tested Under Pressures Far Greater than Normal . . . Prevent Oil Leakage, Assure Long Life and Complete Safety.

3 New Spra-bonderizing Process . . . Plus Triple Coat Automobile Finish Give Tanks Positive Fourway Protection Against Attacks of Rust and Corrosion.

"I Like Its Six Big

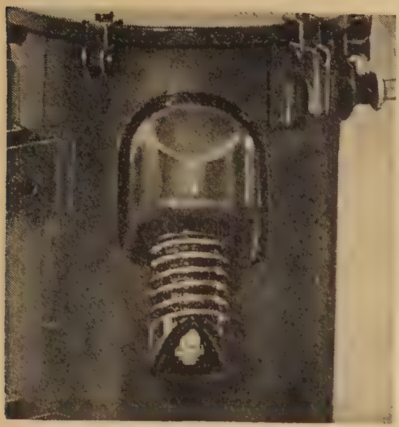
You'll Like The Engineering Advancements Built Into the New Allis-Chalmers Distribution Transformer to Give You Easier Installation . . . Greater Dependability . . . Money-Saving Operation!

It's here! The transformer you helped us design — the new Allis-Chalmers EEI-NEMA Distribution Transformer!

By pooling the knowledge of hundreds of operating men all over the country, it has been possible to design a transformer that makes your specifying and buying easier . . . a simplification

ALLIS-CHALMERS DISTRIBUTION

ALLIS-CHALMERS DISTRIBUTION TRANSFORMER



4 Extra-heavy Porcelain Coordinated Bushings with Liberal Creepage Offer Maximum Reliability Under Fog, Dust, Chemical or Other Adverse Conditions.

5 Double Conductor Insulation . . . Flexible Enameled Wire . . . Plus the Added Protection of Well-Lapped Cable Paper Provide Double Safety Against Winding Failures.

6 Improved Core and Coils, Liberally Designed with No Manufacturing Short Cuts . . . Mean Extra Years of Service-free Performance Under All Types of Operating Demands.

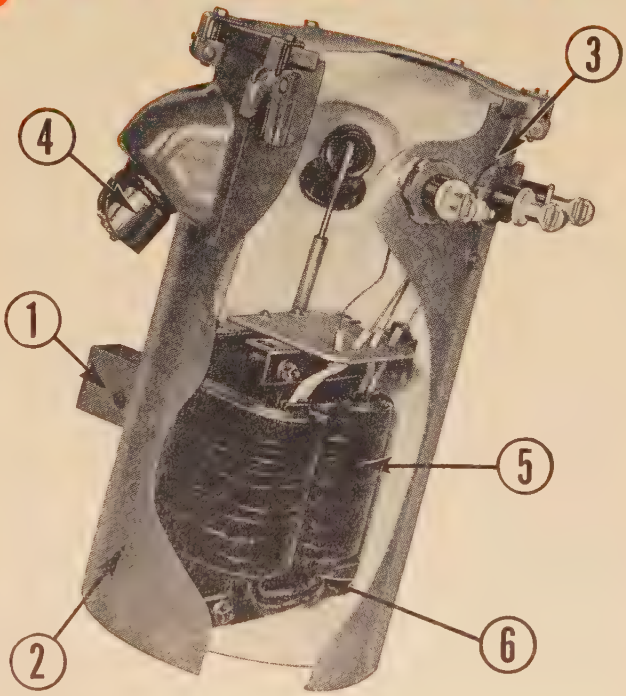
Engineering Features!"

that will undoubtedly save thousands of dollars, not only in first cost, but in operating expenses as well.

How is this done? By standardizing the location of supports and bushings, all sizes and makes are now completely interchangeable. This means you can get faster deliveries . . . easier installation. It also means fewer parts and fewer complete units for you to handle in stock.

Remember, too, Allis-Chalmers cuts no corners in its manufacturing process. Advanced engineering . . . plus the best material and skilled workmanship . . . give you built-in quality second to none.

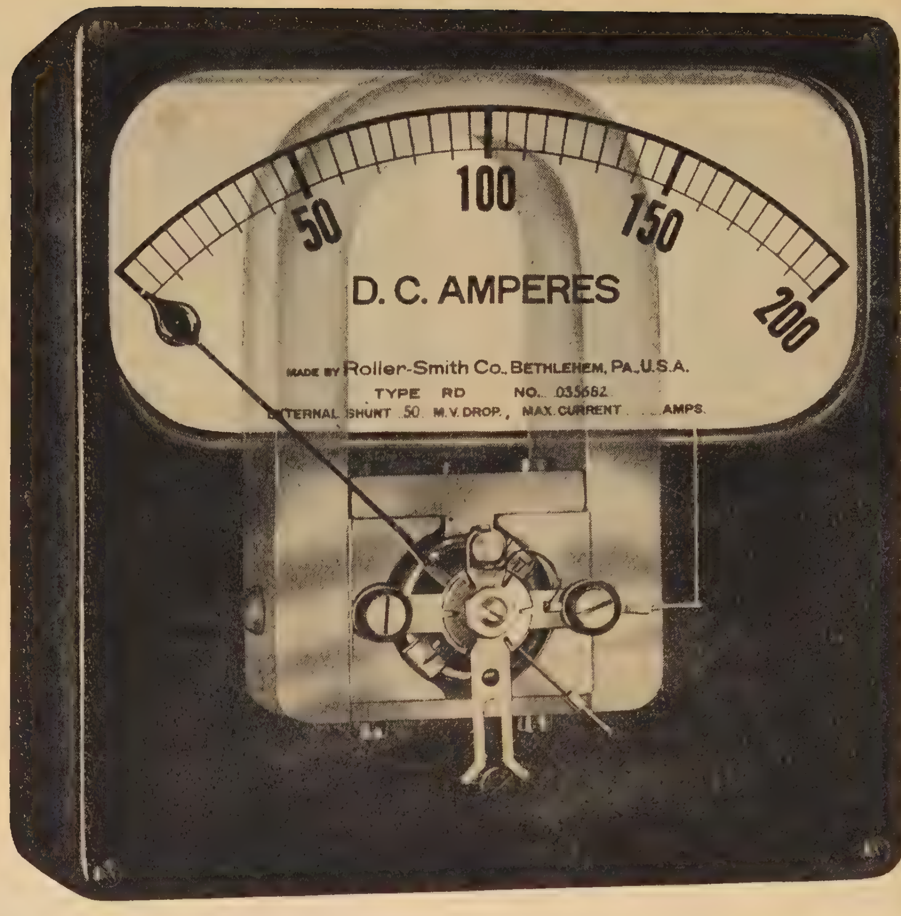
For complete engineering information on the new Allis-Chalmers EEI-NEMA Distribution Transformer, call the district office near you. Or write for your copy of our new Bulletin B-6159. Allis-Chalmers Mfg. Co., Milwaukee, Wisconsin.



A-1382

TRANSFORMERS *Cut Operating Costs*

LOOK Behind the Dial



ROLLER-SMITH
SWITCHBOARD INSTRUMENTS

Direct Current

Ammeters
Voltmeters
Milliammeters
Millivoltmeters

Alternating Current

Ammeters
Voltmeters
Wattmeters
Frequency Meters
Power Factor Meters
Synchroscopes
Rectangular Triplex Ammeters
Horizontal Edgewise Triplex Ammeters

—and you'll find this Roller-Smith D.C. switchboard ammeter a sturdily built, yet highly sensitive instrument.

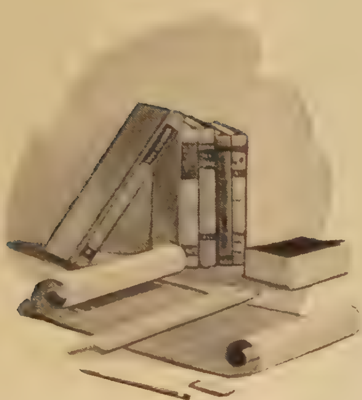
Its design has been balanced to give best overall performance. The tungsten steel magnet is generously proportioned. The permanent magnet moving coil mechanism is effectively damped. Sturdy bridge construction assures accurate spacing and permanent calibration. The features found in the d-c ammeter are typical of the complete Roller-Smith line of a-c and d-c switchboard instruments. Get complete information today from our nearest representative or write Roller-Smith, Bethlehem, Pennsylvania.

ROLLER SMITH

Electrical Measuring and Protective Apparatus

ROLLER-SMITH COMPANY BETHLEHEM, PENNA.

Switchboards • Metal Enclosed Switchgear • Electrical Instruments
Indoor and Outdoor Oil Circuit Breakers • Air Circuit Breakers



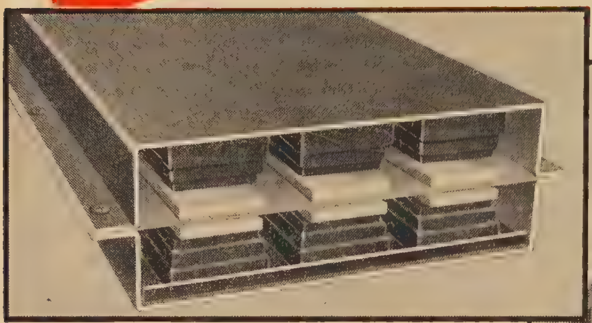
If you'll abandon all idea of what high voltage station insulators have always looked like...set out to design a unit best calculated to meet operating requirements . . . find a plant capable of producing your design with mechanical soundness . . . test it ten years on operating systems coast to coast . . . then, and only then, you'll have an insulator that offers the operating advantages characteristic of the Lapp Station Post.

Lapp

LAPP INSULATOR COMPANY, INCORPORATED • LE ROY, N. Y.

PIONEERS & SPECIALISTS in ENCLOSED

"LO-X" (Low Reactance) TYPE FOR MAIN FEEDERS



End view of a three-phase section of "LO-X" Bus Duct with conductors so arranged and proportioned that magnetic field is minimized with resultant low losses. This design also permits the use of a rugged steel casing giving greatly increased mechanical strength with no sacrifice of electrical efficiency.

At right. Bull Dog Feeder Type BUStribution DUCT used as a riser from outside transformers. Loads are tapped off at each floor and distributed through panelboards or Bull Dog "Plug-in" Type BUStribution DUCT.

"LO-X," the latest addition to Bull Dog's Flexible Electrical Distribution Systems, is the most efficient design available in current-carrying conductive systems for heavy currents. Here for the first time is a busbar system which assures the industrial user of ample voltage at the point of application, wherever and whenever needed.

"LO-X" is designed especially for the most efficient distribution of current in the conductors, and for the most effective heat dissipation characteristics. The result is greater current-carrying ability, lower operating temperatures, and less voltage drop due to reactance.

"LO-X" may be used alone, or it may be combined with Bull Dog's "Plug-in" Type BUStribution DUCT, and associated fittings. Whatever the installation, "LO-X" affords a high load capacity, better voltage regulation, greatly reduced line drop, and consequently more efficient and uniform operation.

"LO-X" is available in from 500 to 4,000 amp. capacity, 600 volts or less, single phase, three phase, and three phase 4 wire.

Note in the illustration above how the 2,000-ampere "LO-X" BUStribution DUCT leaves the Transformer Room, thence through Main Breaker in Switch Room, and out through the wall into the factory where, as shown at the right, it extends the entire width and depth of the plant. Cable Tap Boxes as shown in the illustration at right may be located at ten-foot intervals along the DUCT.

★

MANUFACTURERS OF VACU-BREAK SAFETY SWITCHES, CIRCUIT MASTER AND

BUSBAR DISTRIBUTION SYSTEMS

"PLUG-IN" TYPE with Outlets for Branch Circuit Plugs

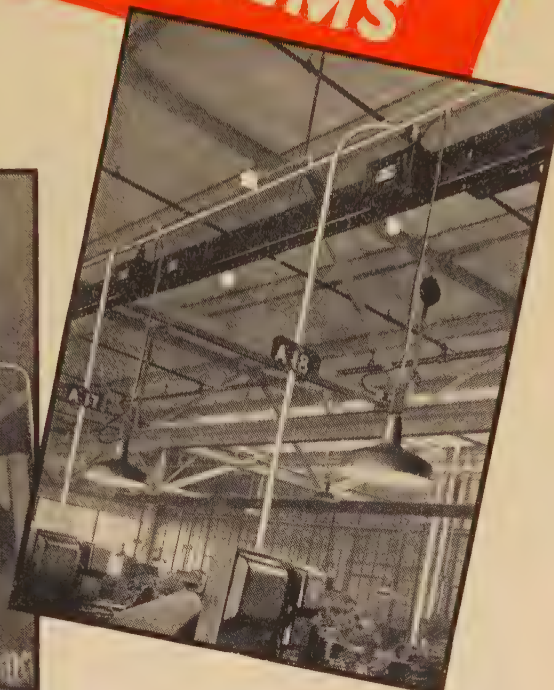
Bull Dog "Plug-in" Type BUStribution DUCT is widely used not only for branch runs from the "Feeder" Type DUCT, but for complete specialized installations. Its standard ten-foot sections, with ten outlet openings to each section offer the widest latitude in machine arrangement and flexibility.

The "Plug-in" line includes every necessary type of associated fitting—elbows, tees, and crosses—together with a wide variety of Branch Circuit Plugs, Circuit Breaker Plugs, Bus Swing Plugs, etc. "Plug-in" Type BUStribution DUCT is available with either two or three conductors, in capacities from 125 to 1,500 amperes, 600 volts or less.

For complete information on all Bull Dog Busbar Systems — BUStribution DUCT, Universal and Industrial Trol-E-Duct — send for complete descriptive bulletins, or better yet, ask to have a Bull Dog sales engineer call on you.

BULL DOG
ELECTRIC PRODUCTS CO.
DETROIT, MICHIGAN
•
Bull Dog Electric Products of Canada, Ltd., Toronto, Ontario

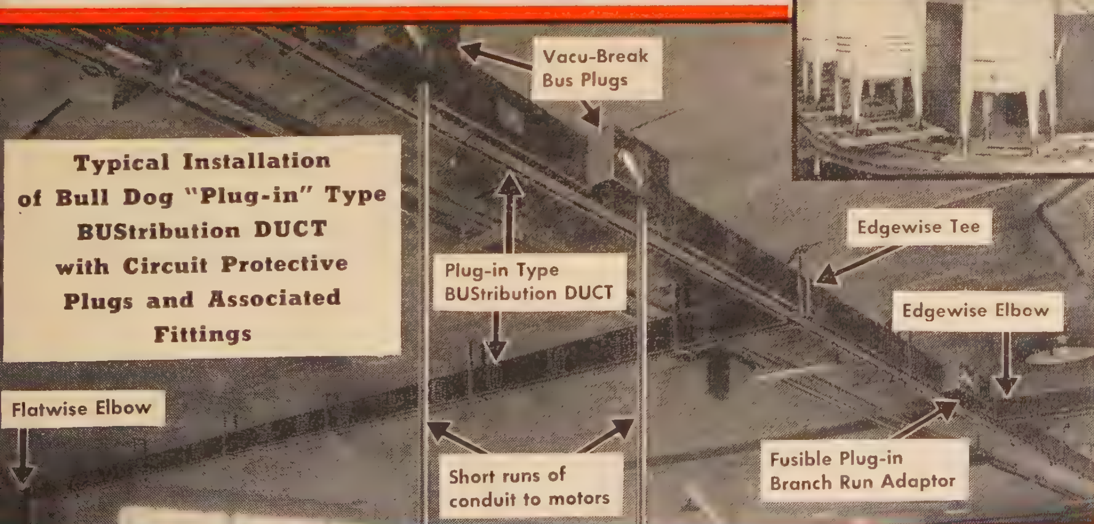
The illustration above shows how conveniently a whole battery of machines may be connected to "Plug-in" BUStribution DUCT. And machine arrangement may be quickly and easily altered at any time, with no delays for rewiring.



An installation of Bull Dog Universal Trol-E-Duct for flexible lighting paralleling the BUStribution DUCT system. Individual lights attached to movable trolleys or twist-out plugs in the duct provide illumination exactly where needed.

Bull Dog Industrial Trol-E-Duct as shown above in the illustration of a washing machine assembly line, provides mobile current and suspension support for portable tools. Industrial Trol-E-Duct is also widely used for monorail hoist and crane systems.

★



AF-TO-FUSE PANELBOARDS, SWITCHBOARDS, DUCT SYSTEMS—FOR LIGHT AND POWER

In the field of Telephony—whether wire or radio—wherever direct current is required from an A.C. source, I. T. & T. Selenium Rectifiers meet the exacting requirements of the art of speech transmission.

The Selenium Rectifier is a compact and extremely light weight unit which requires no maintenance and has practically unlimited life. The outstanding features in its application to Telephony are: high efficiency of rectification . . . extremely low back leak . . . high permissible ambient temperatures . . . flexibility of voltage and current output for test equipment.

AMONG OUR CUSTOMERS

American Telephone and Telegraph Company • Auth Electrical Specialty Co., Inc. • Bell Telephone Laboratories, Inc. Graybar Electric Company, Inc. • Kellogg Switchboard & Supply Company • The North Electric Manufacturing Company • Raytheon Manufacturing Company • Rochester Telephone Company • The Gray Manufacturing Company Western Electric Company

Consulting engineering services available for specific requirements.
Address Technical Department for descriptive bulletin.

INTERNATIONAL TELEPHONE DEVELOPMENT CO., INC.
67 Broad Street, New York, N. Y.

DELIVERIES—
NOT PROMISES!

LOW COST
CLIPON AMMETER

..Perfect Balance
..Light Weight
..Completely Insulated Jaws
..±2% Accuracy

LIST $80.

DUAL RANGE
0-100/500 AMPS

..Large 2¼″ Square Opening
..Long Open Scale
..50 Scale Divisions
..10 Years' Proven Service

ALSO MULTI RANGE CLIPON AMMETER 0-10/25/100/250/1000 AMPS.
LIST $120.

PHASE ROTATION INDICATOR

..Instant Indication of Phase Rotation
..110/550 Volts
..2½″ Portable Pocket Model
..Complete with Heavy Insulated Leads
..Heavy Clips with Rubber Guards
..Also Flush and Surface Types

LIST $60.

LOW COST

LIGHT WEIGHT

NEW HIGH ACCURACY PORTABLE VOLTMETER

..0–150/300/750 Volts
..Long 5¼″ Scale
..½ of 1% Accuracy
..AC-DC
..Hand Calibrated Mirror Scale
..150 Scale Divisions
..Frequency 15–135 cps.
..Hinged Cover with Leather Carrying Handle
..Light Weight—Robust Construction
..Conforms to A.I.E.E. and N.E.M.A. Specifications

MADE IN U.S.A.

LIST $66.

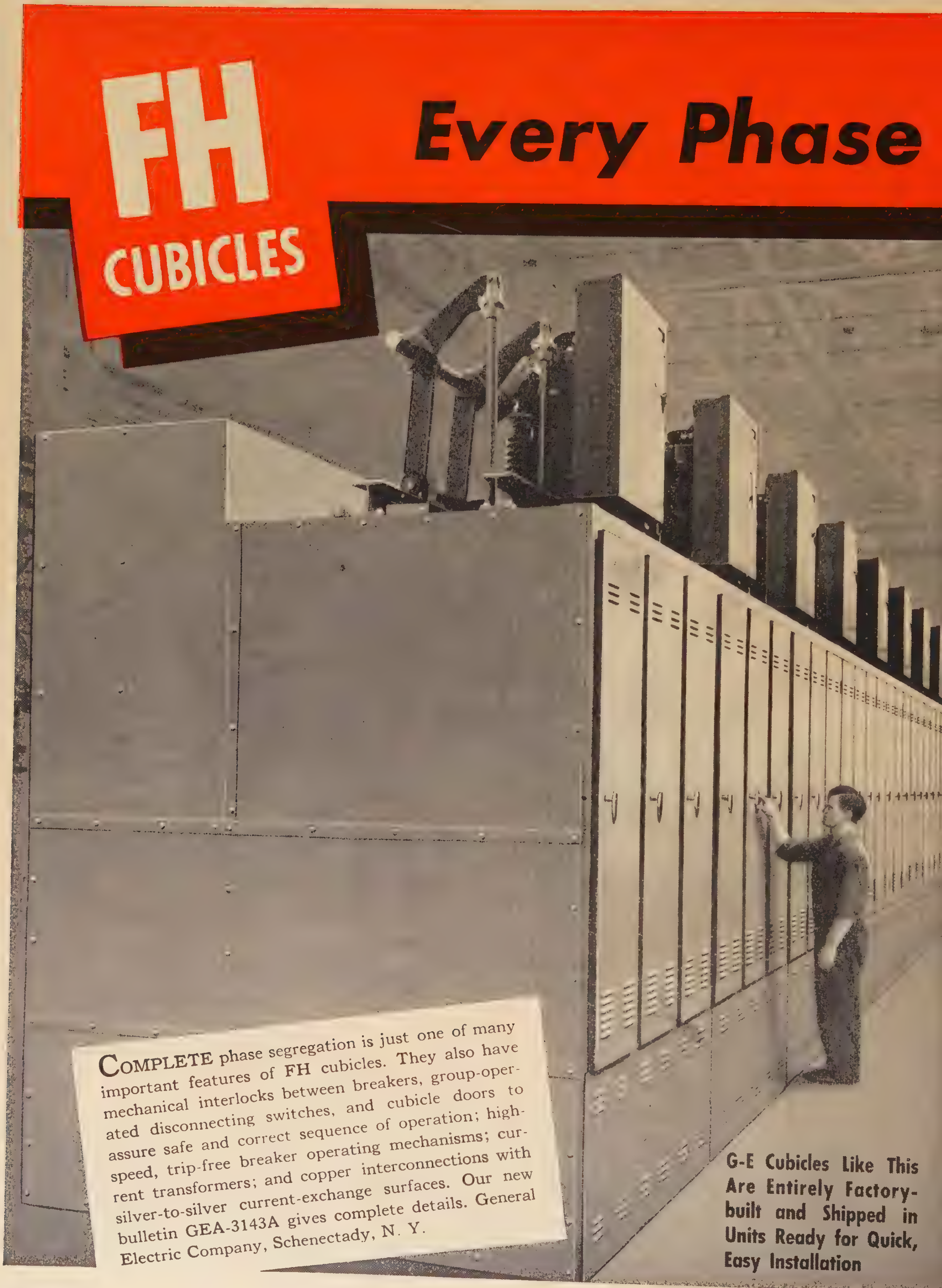
NO DELAY

All Instruments Available Immediately from Stock

We can also give *immediate* deliveries on your requirements for Special Transformers, etc., etc.

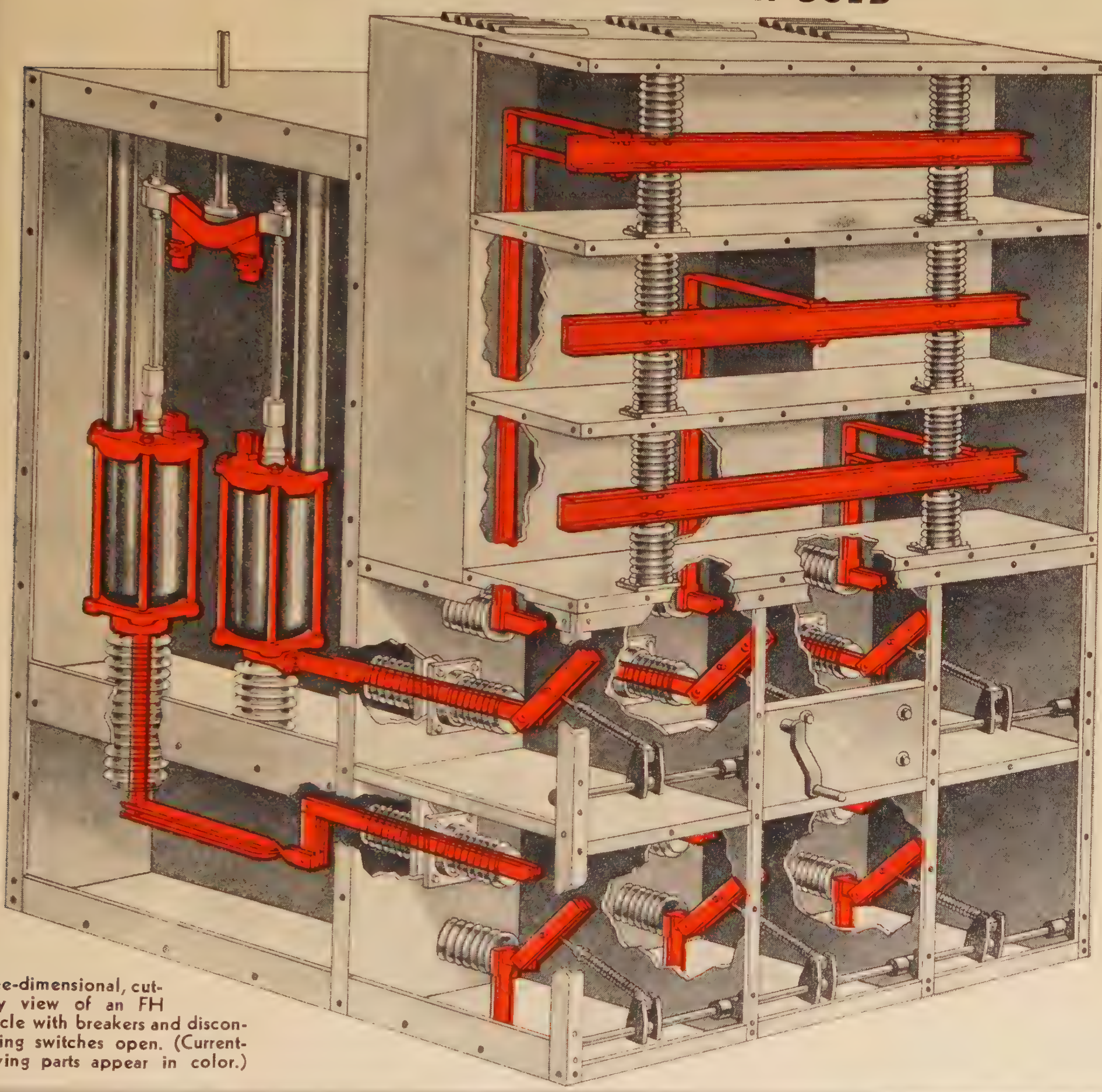
FERRANTI ELECTRIC, INC. 30 Rockefeller Plaza New York, N.Y.

Ferranti Electric, Ltd., Toronto, Canada • Ferranti, Ltd., Hollinwood, England


FH
CUBICLES
Every Phase
COMPLETE phase segregation is just one of many important features of FH cubicles. They also have mechanical interlocks between breakers, group-operated disconnecting switches, and cubicle doors to assure safe and correct sequence of operation; high-speed, trip-free breaker operating mechanisms; current transformers; and copper interconnections with silver-to-silver current-exchange surfaces. Our new bulletin GEA-3143A gives complete details. General Electric Company, Schenectady, N. Y.
G-E Cubicles Like This Are Entirely Factory-built and Shipped in Units Ready for Quick, Easy Installation

Is Wrapped in Steel

Breakers, Disconnecting Switches, and Buses Are Completely Segregated
NO LIVE PARTS ARE EXPOSED

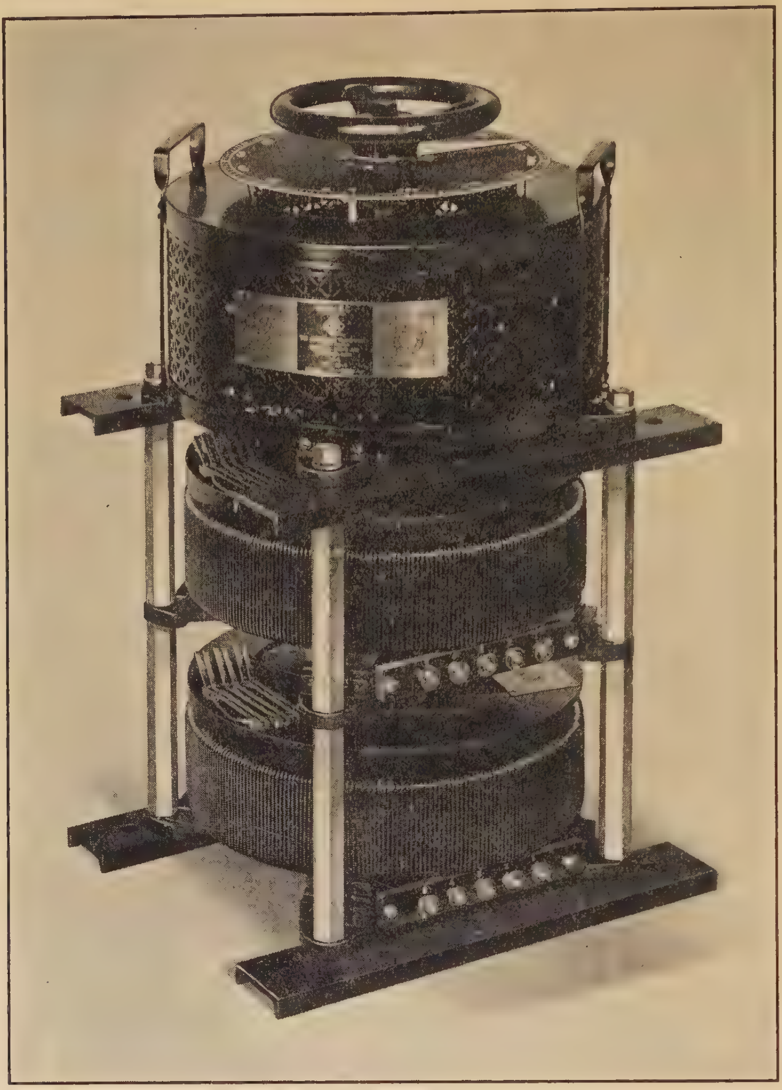


ree-dimensional, cut-
ay view of an FH
bicle with breakers and discon-
cting switches open. (Current-
rrying parts appear in color.)

GENERAL ELECTRIC

855-9-7300

HIGH POWER VARIACS



FOR USE WITH 2- and 3-phase loads, the ganged assemblies of VARIACS offer convenient, efficient, flexible and smooth volume control. Ganged units will handle really high power with all of the advantages found in the single units so widely used throughout the electrical utilities field.

The VARIAC, the original, continuously-adjustable autotransformer, has many advantages over any other manually operated control. Its regulation is excellent; it provides absolutely step-less control of any alternating current up to its full load rating; its efficiency is high; dials are calibrated in output voltage; it will supply output voltages 15% above line voltage; and all VARIACS are conservatively rated.

Specifications for 2- and 3-Phase Variac Combinations

INPUT		OUTPUT			Type of Assembly	Price
		KVA		3-Phase Line Voltage		
3-Phase Line Voltage	Circuit	At Input Voltage	At Max. Voltage			
230	Open Δ	3.6	4.2	0–270	100-RG2	$ 85.00
230	Y	3.6	3.6	0–460*	100-RG3	130.00
230	Y	7.2	7.0	0–270	100-QG3	130.00
230	Open Δ	12.5	9.3	0 270	50-BG2	225.00
230	Y	12.5	8.0	0 460*	50-BG3	335.00
230	Y	18.0	17.5	0 270	50-AG3	335.00
460	Y	7.2	7.2	0 460	100-RG3	130.00
460	Y	25.0	25.0	0–460	50-BG3	335.00

* Open-circuit voltage—regulation is poor for this connection.

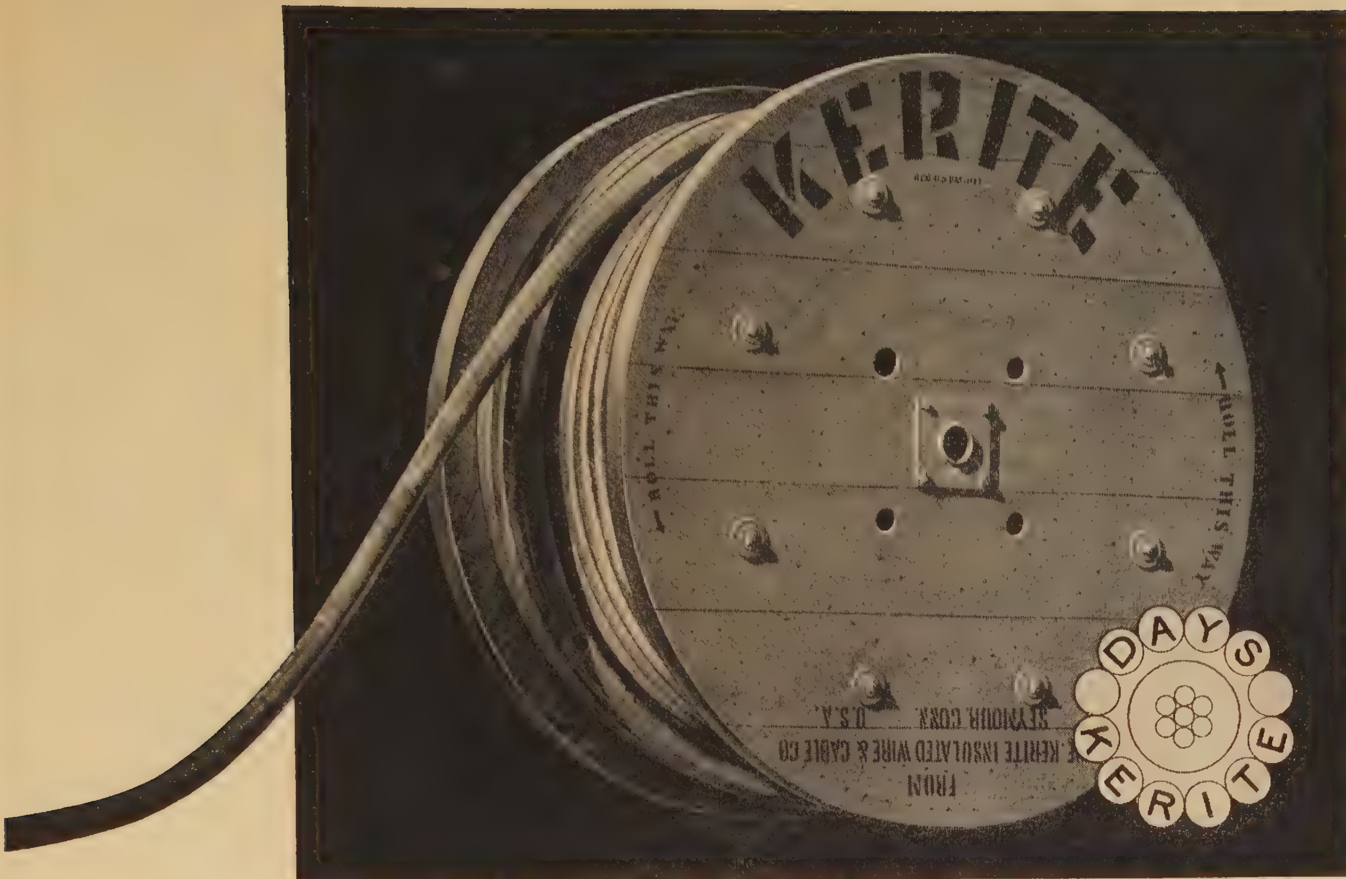
WRITE FOR THE *NEW* VARIAC BULLETIN 706

GENERAL RADIO COMPANY

Cambridge, Massachusetts

Branches in New York and Los Angeles

MANUFACTURERS of PRECISION ELECTRICAL LABORATORY APPARATUS



THE CAREFUL INVESTOR JUDGES A SECURITY
BY THE HISTORY OF ITS PERFORMANCE
KERITE
IN OVER THREE-QUARTERS OF A
CENTURY OF CONTINUOUS PRODUCTION HAS
ESTABLISHED A RECORD OF PERFORMANCE
THAT IS UNEQUALLED IN THE HISTORY OF
INSULATED WIRES AND CABLES

THE KERITE INSULATED WIRE & CABLE COMPANY INC
NEW YORK CHICAGO SAN FRANCISCO

You need the ELECTRONIC SWITCH...

- Multiply several fold the usefulness of your cathode-ray oscillograph with the DuMont Type 185 Electronic Switch!

This handy, portable, moderate-cost instrument provides a switching rate variable from 6 to 2000 times per second. Also operates as square-wave generator over frequency-range from 60 to 400 cycles per second. Here are typical uses:

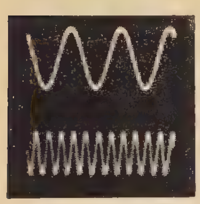


Photo showing comparison of two harmonically related signals on single oscillograph screen, using electronic switch. Patterns displaced for individual observation. Can be superimposed if preferred for very close comparison.

Independence and freedom from interaction of two channels shown in this photo. Illustrates ability of electronic switch to handle sawtooth and sinusoid at same time, and to make them appear as one oscillograph pattern.

Write for **DATA . . .**

- Literature describing DuMont Electronic Switch and DuMont Oscillographs sent on request. Do not hesitate to submit your problems for our specialized engineering collaboration.

DUMONT

ALLEN B. DU MONT LABORATORIES, Inc.

Passaic ★ New Jersey

Cable Address: Wespexlin, New York

Trade Literature

[Mailed to readers free—unless otherwise noted—upon request to companies named]

Instruments.—Catalog I-21. Describes a-c voltmeters, ammeters, galvanometers, milliammeters and other instruments for industrial, electrical and aircraft purposes. DeJur-Amsco Corporation, Shelton, Conn.

Snap-Action Switches.—Catalog, 36 pp. Comprises engineering data on precision snap-action switches and includes dimensions, prices, operating characteristics and applications. Micro Switch Corp., Freeport, Ill.

Switchgear.—Bulletin B-6012A, 24 pp. Describes metalclad, vertical-lift switchgear equipment; includes many installation views as well as dimensions, outline drawings and circuit diagrams. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Reactors.—Bulletin GEA-1090A, 4 pp. Describes oil immersed, current-limiting reactors and the advantages of this type of apparatus for protecting current-conducting equipment. General Electric Co., Schenectady, N. Y.

Miniature Bearings.—Bulletin. Describes new, self-aligning pivot bearings for radial and thrust loads. Such miniature bearings are applicable in instruments of many types. Miniature Precision Bearings, Lebanon, N. H.

Industrial Capacitors.—Catalog 164, 40 pp. Describes capacitors for motor starting and other a-c applications. Discusses capacitor characteristics as related to the requirements for various industrial uses. Cornell-Dubilier Electric Corp., South Plainfield, N. J.

Safety Switches.—Catalog 126, 76 pp. This condensed catalog contains listings and the latest prices of safety switches, service equipment, multibreakers and other circuit breakers, panelboards, motor control and pressure switches. Square D Co., 6060 Rivard St., Detroit, Mich.

Lamp Ballasts.—Catalog. Describes 62 types and sizes of lamp ballasts available for fluorescent lamp application. With the catalog is included Engineering Service No. 57, which contains technical data and information useful to prospective employers of fluorescent lighting. The Acme Electric & Mfg. Co., Cuba, N. Y.

Lightning Arresters.—Cat. Sec. 38-120, 32 pp. Describes station type auto-valve lightning arresters with ratings from 3 to 240 kv. Principles involved in the arrester functions are discussed with a note on protective ratios. An interesting map of the United States showing annual isoceraunics of total thunderstorm days, 1904–1933, is reproduced. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Wiping Solder.—Bulletin. Describes a recently developed wiping solder for cable work, line splicing and other utility applications. This newly introduced, patented product is said to improve workability and to result in smoother, non-porous and uniformly sound joints. The finer grain of the new solder is illustrated and compared with standard preparations. Joseph T. Ryerson & Son, Inc., Chicago.

Strip-Chart Recorders.—Bulletin 570, 16 pp. Describes newly designed instruments used for measuring and recording on a 6-inch strip-chart: d-c amperes and milliamperes, d-c volts and millivolts, pressure, liquid level, flow, mechanical motion, and for remote recording. The Bristol Co., Waterbury, Conn.

Ventilating Fans.—Catalog X4059, 16 pp. Describes exhaust and ventilating fans for commercial, industrial and domestic installations. . . . . **Air Circulators.**—Catalog X4058, 8 pp. Describes ultra-quiet fans, each available with ceiling, wall-bracket, counter-column and adjustable floor column mountings. The Emerson Electric Mfg. Co., St. Louis, Mo.

(Continued on page 22)

CLASSIFIED ADVERTISEMENTS

RATES: Fifty cents per line; minimum charge based on use of five lines; maximum space not to exceed thirty lines. Copy is due the 15th of the month preceding publication date.

ENGINEERS

Large manufacturer in North New Jersey wants mechanical and electrical engineers; widely diversified line of products offers inviting opportunities in development of methods, processes, and machinery for manufacturing and reducing costs. Must be engineering graduates of accredited colleges, high scholastic standing, 5 to 10 years manufacturing experience required; salary commensurate with ability and record of accomplishments; must be U.S. citizens; state age, experience, education, salary desired, attach photograph, not returnable. Address Box 214, ELECTRICAL ENGINEERING, 33 West 39th St., New York City.

WANTED: Graduate Electrical Engineer with substantial experience in design and testing of small and medium sized air cooled transformers, particularly of the high reactance type used with neon signs and for oil burner ignition. Position is one of responsibility with real opportunity for qualified man. Location Middle West. In reply state qualifications and salary desired. Address Box 213, ELECTRICAL ENGINEERING, 33 West 39th St., New York City.

VARNISHED CAMBRIC • RUBBER COVERED POWER CABLES • BUILDING WIRE

SIGNAL CABLE • FLEXIBLE CORDS • ARMORED CABLE

CRESCENT

GENUINE

A.B.C.

ARMORED BUSHED CABLE

CRESCENT INSULATED WIRE & CABLE CO.

1. CONDUCTOR—flame retarding, printed showing size, type of insulation and voltage.
2. BUSHING—easy to insert as paper unwraps from under both ends of armor to make room for the bushing.
3. STEEL ARMOR—low resistance, electrogalvanized giving longest life.
4. Thoroughly tested at several points during manufacture and receiving a final test of 2000 volts between conductors and armor.
5. *CRESCENT has unexcelled facilities for the complete manufacture of Armored Bushed Cable in all its steps. When you buy CRESCENT A. B. C. ARMORED BUSHED CABLE you buy the best. Do not be satisfied with any substitute.*

CRESCENT
WIRE and CABLE
Factory: TRENTON, N. J.—*Stocks in Principal Cities*

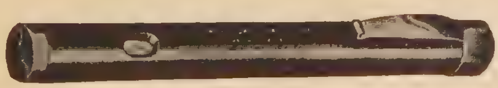
CRESCENT ENDURITE SUPER-AGING INSULATION • WEATHER-PROOF WIRE

• SERVICE ENTRANCE CABLE • MAGNET WIRE •

NOW more than ever protect men and equipment!

use the

Statiscope



FOR A.C.

and KNOW that circuits are alive or dead

•

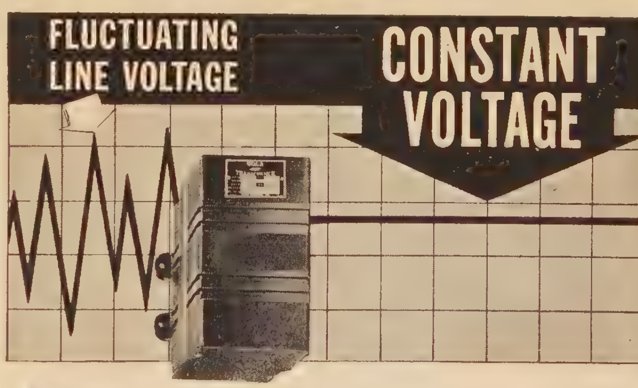
Write for Descriptive Circular

•

MINERALLAC ELECTRIC COMPANY

25 N. Peoria St
CHICAGO, ILL.

50 Church Street
NEW YORK CITY

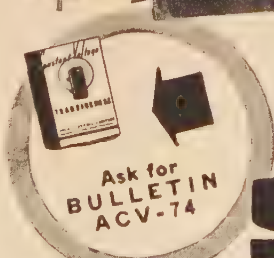


Whether it's 1 VA for an instrument or 10 KVA for a production line—here's constant, stable voltage for you at all times, even though the line voltage varies **as much as thirty percent.**

Fully automatic and instantaneous in operation—no moving parts—require no maintenance—self-protecting against short circuit.

You can build a SOLA CONSTANT VOLTAGE TRANSFORMER into your product, or incorporate it in your production line or laboratory and know that every test will be made under identical line conditions.

Compact—economical. Standard designs are available, or units can be built to your special specifications.



SOLA ELECTRIC COMPANY
2525 Clybourn Ave. Chicago, Ill.

SOLA

Constant Voltage TRANSFORMERS

THE Standards of the American Institute of Electrical Engineers now comprise fifty sections on electrical machinery and apparatus. They are chiefly devoted to defining terms, conditions, and limits which characterize behavior, with special reference to acceptance tests, and many of them are recognized officially as American Standards.

The Standards available are listed below, together with prices. A discount of 50% is allowed to Institute members (except on Nos. C57.1, 2, 3, and C37.4). Such discount is not applicable on extra copies unless ordered for other members. Numbers of the Standards Sections should be given when ordering. A binder (illustrated above) for standards is available, with durable, stiff covers, resembling leather, lettered in gold. Price, $1.75 net.

AIEE STANDARDS

(Figures in Parentheses Give Dates of Latest Editions)

No. 1	General Principles Upon Which Temperature Limits Are Based in the Rating of Electrical Machinery (6-40)	$0.40
4	Measurement of Test Voltage in Dielectric Tests (6-40)	.40
*C50	Rotating Electrical Machinery, (Supersedes Nos. 5, 7, 8, 9, and 10) (4-36)	1.30
**11	Railway Motors (3-37)	.50
C57.1	Transformers, Regulators and Reactors (1940)	
C57.2	Test Code for Transformers, Regulators and Reactors (1940)	
C57.3	Guides for Operation of Transformers (1940) (C57.1, C57.2, C57.3, published as one booklet supersede A.I.E.E. Nos. 12, 13, 14, 100 and Test Code for Transformers. The member discount does not apply on price of this publication which is 75 cents net.)	.75
*15	Industrial Control Apparatus (5-28)	.40
*16	Railway Control Apparatus (1-33)	.40
*17f	Mathematical Symbols (2-28)	.30
*17g1	Letter Symbols for Electrical Quantities (11-28)	.20
**17g2	Graphical Symbols for Electric Power and Wiring (1-34)	.20
**17g3	Graphical Symbols for Radio (1-34)	.20
**17g5	Graphical Symbols for Electric Traction Including Railway Signaling (1-34)	.40
**17g6	Graphical Symbols for Telephone and Telegraph Use (3-29)	.20
*18	Capacitors (6-34)	.20
C37.4	A-C Power Circuit Breakers (1-41) (A proposed revision of No. 19. The member discount does not apply on price of this publication which is 60 cents net.)	.60
19	Oil Circuit Breakers (4-38)	.40
20	Air Circuit Breakers (5-30)	.30
22	Air Switches and Bus Supports (6-40)	.40
*C37.1(23)	Relays Associated with Power Switchgear (1937)	.40
*C37.2(26)	Automatic Stations (1937)	.40
27	Switchboards and Switching Equipment for Power and Light (10-30)	.30
27A	Switchgear Assemblies (2-41) (A proposed revision of No. 27. No charge.)	
*28	Lightning Arresters (3-36)	.30
*30	Wires and Cables (4-37)	.40
*C39.1(33)	Electrical Indicating Instruments (7-38)	.40
*36	Storage Batteries (2-28)	.20
*38	Electric Arc Welding Apparatus (1-34)	.40
*39	Electric Resistance Welding Apparatus (1-34)	.30
*41	Insulator Tests (3-30)	.30
41A	Insulator Tests (3-41) (A proposed revision of No. 41. No charge)	
45	Recommended Practice for Electrical Installations on Shipboard (7-40)	1.50
*46	Hard Drawn Aluminum Conductors (6-27)	.20
*C8.5	Specifications for Cotton Covered Round Copper Magnet Wire. (See C8.7 for price.)	
*C8.6	Specifications for Silk Covered Round Copper Magnet Wire. (See C8.7 for price.)	
*C8.7	Specifications for Enameled Round Copper Magnet Wire. (C8.5, 8.6 and 8.7 published as one pamphlet) (1936)	.30
**C8.11	Code Rubber Insulation for Wire and Cable for General Purposes (1936)	.20
**C8.12	Cotton Braid for Insulated Wire and Cable for General Purposes (1935)	.20
**C8.16	Tree Wire Coverings (1936)	.20
**C8.17	Class AO 30 Per Cent Rubber Insulation for Wire and Cable for General Purposes (1936)	.20
**C8.18	Weather Resistant Wire and Cable URC Type (1936)	.20
*C8.19	Weather Resistant Saturants and Finishes for Aerial Rubber Insulated Wire and Cable (1939)	.20
*C8.20	Heavy Wall Enameled Round Copper Magnet Wire (1939)	.20
**72	Specifications for Weatherproof Wires and Cables. (See No. 73 for price.)	
**73	Specifications for Heat-Resisting Wires and Cables. (Nos. 72 and 73 published as one pamphlet) (9-32)	.20
500	Test-Code for Polyphase Induction Machines (8-37)	.50
520	Test Code for Apparatus Noise Measurement (3-39)	.30
	Total Cost of Complete Set	$15.35

* *Approved as American Standard*

** *Approved as American Tentative Standard*

SECTIONS IN PREPARATION

Seven such sections are now available in report form for purpose of criticism, and copies will be sent without charge upon request. These sections are as follows:

No. 6	Mercury Arc Rectifiers.
21	Apparatus Bushings (3-41) (Including Test Code)
24	Protector Tubes
25	Fuses Above 600 Volts.
17g1A	Letter Symbols for Electric and Magnetic Quantities.
501	Test Code for D-C Machines.
40	Electrical Recording Instruments.
—	Test Code for Synchronous Machines.

American Institute of Electrical Engineers 33 West 39th Street: New York

THE NIGHTMARE OF THE TWO USELESS CONVERTERS

Or, what's all this about Fiberglas* for preventive maintenance?

A MANUFACTURER of electrical products was having nightmares.

He'd dream that his two 500 K.W. rotary converters both broke down *at once*, and he'd wake up in a cold sweat, because his plant had 750 D.C. motors depending on those converters for current!

Sure, the converters had been working okay for more than 15 years. But suppose they gave up the ghost *now?* The motors would be useless!

Besides, the plant was running 24 hours a day, seven days a week on defense orders! Production would stop; plant profits would go out the window; and the cost would be enormous. No wonder the manufacturer had nightmares.

So what did he do?

To be on the safe side, this manufacturer insulated his converters, one after another, with Fiberglas Electrical Insulation . . . *to get the higher safety factor Fiberglas provides!*

And that, Sir, is the smartest kind of preventive maintenance!

Perhaps you have electrical equipment which has never been troublesome or expensive because of breakdowns. Even so, that equipment is probably running extra hours now—on defense work. The danger of downtime is there; and one of the best ways to guard against it is to insulate with Fiberglas.

For instance . . .

Rewinding your standard-size, Class A motors with Fiberglas will give you the *maximum* safety factor!

Get Fiberglas Motors

If you intend to buy new motors, specify the Fiberglas-insulated lines made by leading motor manufacturers. These motors can be supplied in smaller frames than present Class A-insulated motors of the same H.P.! Yet they operate safely at the resulting approved higher temperatures, and . . . *still have a substantially higher safety factor!* The cost is a little more in some instances—no more in others.

Case history after case history shows how remarkably Fiberglas has outlasted other insulations . . . *cutting operating costs on the toughest jobs!*

Where Fiberglas Saves

Today, you'll find Fiberglas saving money on equipment that works under conditions of high temperature, moisture, corrosive fumes, dirt, and even many acids. That's why many of the best-known names in industry *use* Fiberglas Electrical Insulation, and consider it excellent insurance against downtime.

On your own new equipment, and on repair jobs, get the advantages of Fiberglas. Specify it! *Owens-Corning Fiberglas Corporation, Toledo, Ohio. In Canada: Fiberglas Canada, Ltd., Oshawa, Ontario.*

OWENS-CORNING

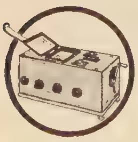
FIBERGLAS*

*T. M. Reg. U. S. Pat. Off.

TO ELECTRICAL ENGINEERS: The case histories published in this series of advertisements show how Fiberglas has proved to be a superior form of electrical insulation. It may well do the same work for you on your own applications. Write for technical information.

"MEGGER"
TRADE MARK REGISTERED U.S. PAT. OFF.
Insulation Testers, Ground Testers and Ohmmeters

In Stock . . .
for the Protection of Your ELECTRICAL EQUIPMENT



We have, in our Philadelphia warehouse, a large stock of "Megger" instruments for measuring Insulation Resistance, Ground Resistance and Conductor and Contact Resistance.

Write for descriptive Catalogs 1685-EE and 1645-EE.

James G. Biddle Co.
1211-13 ARCH STREET *Electrical and Scientific Instruments* PHILADELPHIA, PA.

Trade Literature

(Continued from p. 18)

Drafting Standards.—Bulletin, 32 pp. "Drafting Standards—Accepted and Proposed". Contains the complete drafting standards of ASME and American Welding Society, as well as one page of proposed standards not yet accepted by ASA and not yet published elsewhere. Welding symbols are included. The book will be sent to draftsmen, designers and educators upon request on company stationery. Chas. M. Higgins & Co., Inc., 271 Ninth St., Brooklyn, N. Y.

Cable Installation Equipment.—Catalog, 24 pp. Describes conduit rods, rod adapters and pullers; cable reel jacks, feeders and drawing-in protectors, cable benders, cable racks, manhole guards, ladders and cover hooks, concrete cutters; laying, test and flexible mandrels and other conduit tools. Price list is included. T. J. Cope, Inc., 6120 Vine St., Philadelphia, Pa.

Fuse Cutouts.—Bulletin 215, 32 pp. A comprehensive outline of the principle of "Semafor Ejector" and other type cutout design and operation. Profusely illustrated and diagrammed. Method of cutout selection for any required service is described. Typical installations are shown. Schweitzer & Conrad, Inc., 4435 Ravenswood Ave., Chicago, Ill.

Distribution Transformers.—Bulletin B-6159, 16 pp. Describes new standard distribution transformers that meet all recommendations in first report of the EEI-NEMA joint committee on transformer standards. Design and construction features are covered, as well as dimensions, price lists, and electrical data for sizes of $1^1/_2$ kva to 25 kva for standard voltages of 2,400 to 13,200 inclusive. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Bushing Test Set.—Catalog E-54(4), 12 pp. Describes new portable equipment for measuring the power factor and capacitance of installed bushings, insulators and other high-voltage dielectrics. The equipment is immune to electromagnetic and electrostatic stray-fields; reads directly in terms of capacitance and power factor; and it is unnecessary to apply correction factors at the normal test voltage of 10,000 volts. Leeds & Northrup Co., 4934 Stenton Ave., Philadelphia.

Insulating Varnishes.—Bulletin, 34 pp. The purpose of this manual is to assist the user in the proper selection and application of insulating varnishes. All varnishes usually required are described in sequence based upon their relative importance, in terms of extent and variety of use, including 31 different Harvel and other insulating varnishes, paints and enamels, giving the characteristics, uses, applications, and types. Profusely illustrated with pictures, charts and useful tables. Irvington Varnish & Insulator Co., Irvington, N. J.

FLAT BAR CONNECTORS
by
Burndy

1 TYPE RT—T-Connector for copper tube to flat bar
2 TYPE FE—End Connector for copper tube to flat bar
3 TYPE FD—Stud Connector for flat bar to stud
4 TYPE FDA—Stud Connector for flat bar to stud
5 TYPE QAF—T-Connector for flat bar to cable
6 TYPE FTA—T-Connector for flat bar to cable
7 TYPE HF—H-Clamp for flat bar to flat bar
8 TYPE FDR—Stud Connector for flat bar to stud

For complete listing, write for Catalog No. 40

•

BURNDY
ENGINEERING CO., INC.
459 E. 133 ST. • N. Y. C.

COPPERWELD DEPENDABILITY for all these TRANSMISSION LINE COMPONENTS:

TRANSMISSION CONDUCTORS
COPPERWELD

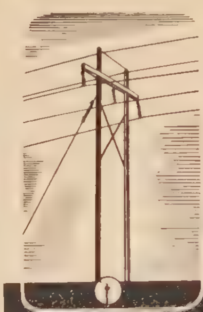
OVERHEAD GROUND WIRE
COPPERWELD

GUY STRAND
COPPERWELD

GROUNDING WIRE AND STAPLES
COPPERWELD

GROUND RODS AND CLAMPS
COPPERWELD

ALSO COPPERWELD ANCHOR RODS, SPLICING SLEEVES, TIE WIRE, AND NAILS



Copperweld

PERMANENTLY MOLTEN-WELDED COPPER EXTERIOR SURROUNDING AND PROTECTING STEEL CORE

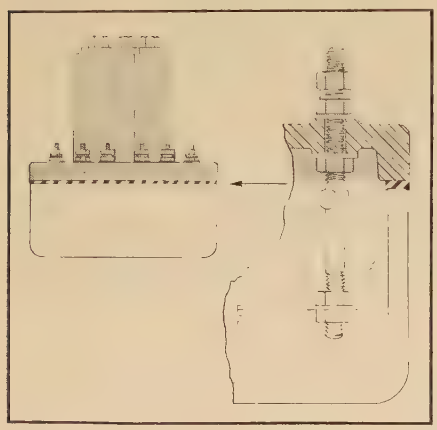
COPPERWELD STEEL COMPANY *Glassport, Pa.*

No. 2 of a Series

PROBLEM: To seal a railway signal relay housing and prevent corrosion of the silver contact points

SOLUTION: Compressible gaskets of Armstrong's Corprene DC-113

A MANUFACTURER of flasher relays, used with railway crossing signals, was troubled with corrosion of the silver contact points in his product. The top plate of his equipment was made of molded bakelite, and the main housing of molded glass. Sealing the uneven surfaces between these two materials called for a soft gasket. Rubber-like materials were tried, but these extruded badly when the flange bolts were drawn down sufficiently to effect a tight joint. In addition, the free sulphur in these compounds seriously corroded the silver contacts. Other gasket materials permitted the entrance of corrosive gases which damaged the silver points.



Corprene Goes to Work

Then Armstrong's Corprene DC-113 was tried . . . and the manufacturer's sealing problems were over! Since this material is truly compressible, no extrusion now occurs when the flanges are tightened. Since it is impervious to liquids and gases, an hermetic seal is now assured. Since it contains no free sulphur, the silver contact points now remain bright and clean.

What's Your Sealing Problem?

More than two dozen Corprene (cork-and-synthetic-rubber) compositions are available—in sheets, cut pieces, and molded parts. The physical properties of these materials can be accurately controlled to meet stringent "special case" requirements. That's why, today, Corprene is licking tough sealing problems in transformers, switches, potheads, cables, circuit breakers, and other electrical equipment. So—if you're anxious to end *your* sealing woes, write Armstrong Cork Company, Industrial Division, 943 Arch Street, Lancaster, Pennsylvania.

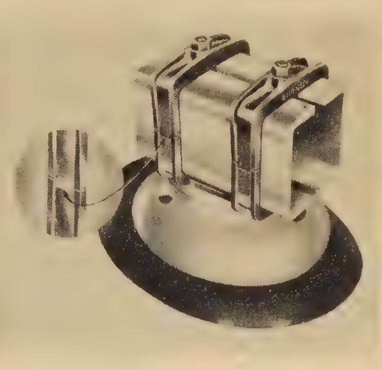
ARMSTRONG'S Corprene

COMPOSITIONS OF CORK AND RUBBER-LIKE MATERIALS

Write for Details

New Products

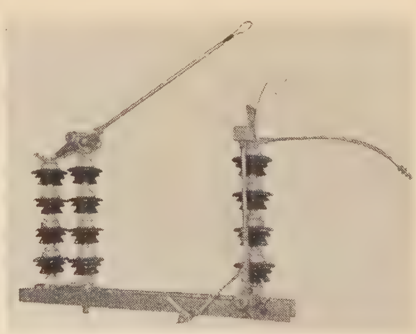
Bus Support Clamps.—The type BH bus support clamp developed by the Burndy Engineering Co., 459 East 133rd St., New York City, is shown assembled to provide a rigid support for channel bus bar. The circled inset illustrates the position of the



clamp when a slide fit on the conductor is desired. This device may be used alternatively as a slide fit support or as a rigid support by simply clamping the caps in the desired position. Center clamping studs and guide ridges insure proper spacing of the copper channels.

Fibre Glass Adhesive Tape.—The Industrial Tape Corporation, New Brunswick, N. J., has developed a fibre glass adhesive tape with a pressure sensitive coating. The new product is expected to find many applications in the electrical industry, and for insulating other than electrically. The tape is manufactured in rolls in the full width of 40 inches and then cut into any desired widths, exactly as paper-backed and cloth-backed tapes are cut.

Balanced Blade Switch.—The illustration shows a single pole element of an improved type high pressure contact 3-pole switch, equipped with grounding blade and wire guides, introduced by the Delta-Star Electric Co., 2400 Block, Fulton St., Chicago, Ill. The main blade is shown in partially open position, particularly to illustrate its full control and balancing in all positions. The main blade has high pressure contacts at both ends. No flexible braids are used and as the back-up springs carry no current they cannot anneal or lose resilience. Rating is 161 kv, 600 amperes, main and grounding blade.



Oil Insulated Magnetic Contactor.—The development of a line of magnetic contactors, insulated with transformer oil, for use on circuits carrying as high as 5,000 volts and as high as 15 amperes, has been announced by Peerless Laboratories, Inc., New York City. The unit is enclosed in a housing 7 by 8 by 4 inches, and is available up to two normally closed circuits and two normally open circuits. The magnet coil may be operated on either 120 or 220 volts, a-c or d-c, and draws less than 10 watts, thereby making it suitable for use on tube circuits. The standard unit is intended for stationary service. For mobile applications it can be supplied completely sealed and furnished with expansion bellows. According to the manufacturer, the unit is applicable wherever high voltage remote control switching and compactness are important factors.

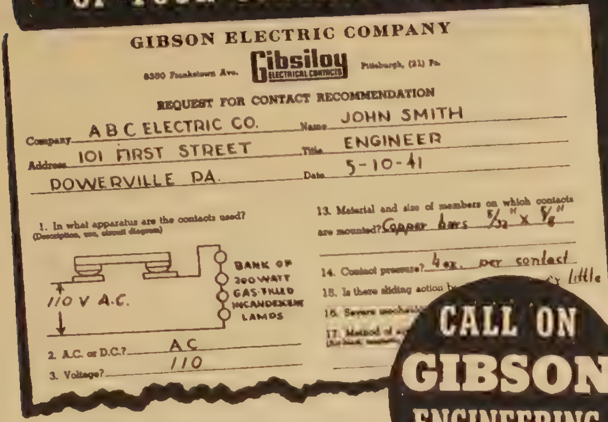
Relay.—A 4-pole, double throw relay is the newest addition to the line of type "C" relays manufactured by the G-M Laboratories, of Chicago. One of its outstanding features is precise machine assembly of parts, which makes for economical quantity production. Operating voltages under

normal conditions range from 2 to 230 volts a-c and 2 to 125 volts d-c. Normal contact capacity is 10 amperes on non-inductive a-c loads, but special contact materials for specific applications may permit the control of considerably higher current.

Dry Developer Paper Free for Test.—To owners of ammonia vapor machines who care to cooperate in the "field trial" test under working conditions, The Frederick Post Co., P.O. Box 803, Chicago, is delivering a stock of "VAPOpaper" without charge, asking only a brief report on its performance in return. Owners of these dry developer machines may secure a trial stock of the new paper by sending the model or serial number of their machines to the paper manufacturer. Among the improvements claimed for the new paper are: 50% rag content bond against sulphite stock used in existing papers; two "speeds" in sensitivity—regular and fast; two colors—blue and red. The new sensitizing medium is said to print out to a cleaner, whiter background and at the same time leaves all lines in deeply colored contrast.

(Continued on page 26)

FOR A THOROUGH ANALYSIS OF YOUR CONTACT PROBLEMS


GIBSON ELECTRIC COMPANY
8350 Frankstown Ave. Gibsiloy ELECTRICAL CONTACTS Pittsburgh, (21) Pa.
REQUEST FOR CONTACT RECOMMENDATION
Company A B C ELECTRIC CO. Name JOHN SMITH
Address 101 FIRST STREET Title ENGINEER
POWERVILLE PA. Date 5-10-41
1. In what apparatus are the contacts used? (Description, use, circuit diagram)

2. A.C. or D.C.? AC
3. Voltage? 110
13. Material and size of members on which contacts are mounted? Copper bars 5/32" x 5/8"
14. Contact pressure? 4 oz. per contact
15. Is there sliding action b... little
16. Severe mechani...
17. Method of ...

CALL ON GIBSON ENGINEERING SERVICE

Modern electrical control equipment imposes severe duties on contacts, which must carry heavy currents without overheating, maintain low resistivity, and open or close high instantaneous currents without burning or welding. To achieve these results under various conditions of current, voltage, inductance, frequency of operation and contact pressure, requires material possessing a wide variety of characteristics. GIBSILOY, produced by powder metallurgy, is made in numerous grades to meet these various and exacting requirements.

What contact material is best suited for your application? For the recommendations of our engineers, send for a copy of the "Contact Questionnaire." No cost or obligation.

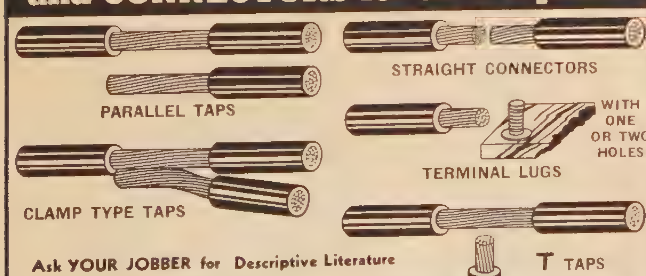
Gibsiloy ELECTRICAL CONTACTS *Manufactured by* GIBSON ELECTRIC COMPANY
8348 FRANKSTOWN AVE., PITTSBURGH (21), PA.

INSULATORS NEED ENGINEERING TOO

Insulators are as much a part of electrical engineering as the size and number of turns of wire, size of core and type of steel. Universal Porcelain engineers are available to assist you in the proper design of your installation requirements This specialized experience can help you

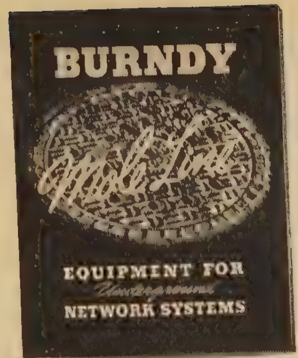
THE UNIVERSAL CLAY PRODUCTS CO.
1550 EAST FIRST ST. SANDUSKY, OHIO

K & H *Solderless Terminal* LUGS and CONNECTORS for all Purposes!



Ask YOUR JOBBER for Descriptive Literature
See Catalog No. 3LC

KRUEGER & HUDEPOHL
Vine at Third Street . . . CINCINNATI, OHIO



BURNDY ENGINEERING *specifies* OIL STOP

FOR OIL TIGHT ELECTRIC INSULATIONS

7 Insert cable ends in Limiter sockets and indent in place with Hypress.
8 Wrap Limiter sockets, cable insulation and about 1 inch of lead sheath with two or three layers of 1/4" varnished cambric tape, coating each layer with Harvel Oil Stop or equal
9 Place Asbestite Shells over Limiter being careful to center the shells on the fusible section

In the Burndy Engineering Catalog on Mole Line Equipment for Underground Net Work Systems, OIL STOP is mentioned on page 13 for use with installations of Burndy Limiters on Oil Impregnated Paper Insulated Cable.

OIL STOP is a phenol-aldehyde synthetic resin which has many uses in the electrical industry for cable splicing, low cost oil tight terminals, stop joints, insulating buses, cementing transformer gaskets, repairing cracked bushings, coil sealing, waterproof coatings, etc.

OIL STOP has the following qualities: completely seals against any kind of oil or water; easily applied as a liquid, yet polymerizes at ordinary temperatures into a firm enduring, infusible insulation—whether exposed to air or not; forms no vapor pockets during polymerization—being free of solvents; will not melt or soften after setting; resists vibration; has excellent adherence to rubber, oil-impregnated paper, molded plastics and fibre; has good adhesion to copper; and is not affected by acid or alkali solutions.

Supplied in the following container sizes: #0 (1/4 pint); #1 (1/2 pint); #2 (1 pint); #3 (1 quart).

Write to Irvington Varnish & Insulator Company, Department 36 for complete information on this unusual insulation.

STANDARD OF THE WORLD IRVINGTON INSULATION TRADE MARK
IRVINGTON VARNISH & INSULATOR CO.
IRVINGTON, NEW JERSEY, U.S.A.
PLANTS AT IRVINGTON, N. J. and HAMILTON, ONT., CAN.
Representatives in 20 Principal Cities

SOLAR

SERVES THE SERVICES

Just as nerves control our bodies, communications equipment controls modern warfare. Nerves must not fail; communications must be maintained.

Solar is proud of... and is zealously guarding... the reliability which its Capacitors add to radio and electrical control equipment for the Armed Service Branches of our Government.

IN THE AIR special Solar capacitors function down to -40 C. or at 50,000 feet altitude, and under severe vibration.

ON THE SEA are Solar capacitors which have passed salt-water immersion tests, are corrosion-proof and stabilized.

MOBILE FORCES—Solar capacitors of compact special design can take punishment from extremes of heat and cold and have passed exacting vibration tests,

ARTILLERY — directed from aircraft — or controlled electrically from the ground — gains certainty of action from reliable electrical equipment — including Solar capacitors.

•

Solar reliability is built into all types of electrical condensers for industrial, radio and service applications.

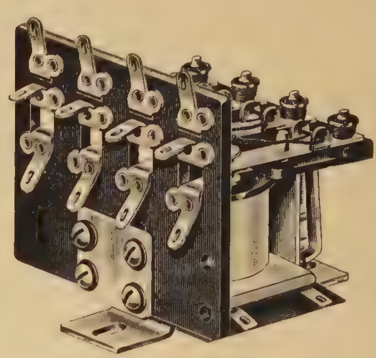
•

SOLAR MFG. CORP. BAYONNE, N. J.

New Products

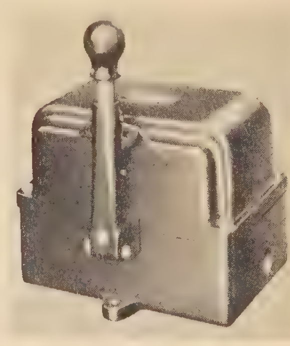
(Continued from p. 24)

Electrical Contacts.—Gibsiloy grade "A" silver-nickel electrical contacts are employed in a line of aircraft battery transfer switches recently built by the Automatic Switch Co., New York, N. Y. These contacts are required to handle 200 amperes at 24 volts d-c, and were chosen for this



application because fine silver contacts would roughen under the severe operating conditions, whereas Gibsiloy retains a smooth, unpitted contact surface. Such contacts approach silver in conductivity, and their high resistance to wear and pitting assures low contact resistance—consequently, low operating temperatures. Gibsiloy grade "A" silver-nickel is one of several ductile contact materials made from powdered metals by the Gibson Electric Co., 8348 Frankstown Ave., Pittsburgh, Pa.

New Cam-Operated Controller.—Speed-up production, through reduced fatigue, is claimed for the new line of cam-operated, mill duty controllers developed by Cutler-Hammer, Inc., Milwaukee, Wis. Extreme ease of operation with positive feel of all speed positions is obtained by using an adjustable compression type of star wheel spring. Available in two-speed, three-speed, and multi-speed types, the controllers are suitable for mill auxiliaries, crane hoist, bridge, and trolley applications. Contacts are vertical, double break, silver-to-silver; the cam shaft operates on sealed ball bearings. An easily accessible terminal board simplifies installation and service, and a heavy cast case and cover, for either separate or benchboard mounting, provide protection from dust and mechanical injury. Optional features include: spring return, off-position latch, two, three or five speeds.



"Thanks again for helping us out"

HERE'S AN EASY WAY TO SOLVE YOUR ELECTRICAL SHEET PROBLEMS

CARNEGIE-ILLINOIS maintains a trained staff of electrical sheet specialists, whose job it is to work with manufacturers of electrical equipment. These men are backed by the experience accumulated in over 37 years of manufacturing silicon steel sheets for electrical use. Their services are always at your disposal.

Many manufacturers have profited from this service by increasing plant efficiency and product quality—by lowering production costs. With peak production schedules, rapidly changing designs and the constant necessity of maintaining and improving the quality of your product, you cannot afford to guess.

Why not call in the man from Carnegie-Illinois when you have problems involving the use of electrical sheets—or talk things over with him before these problems become acute? He knows which sheet grade will give the best performance, the right electrical properties—how to specify the proper grade and the most economical size to use. He is familiar with the problems of annealing and core plating. It won't cost you a cent and may save you a lot of money and production grief.

ELECTRICAL STEEL SHEETS

for motors, generators and transformers

CARNEGIE-ILLINOIS STEEL CORPORATION

Pittsburgh and Chicago

Columbia Steel Company, San Francisco, *Pacific Coast Distributors* · Scully Steel Products Company, Chicago, *Warehouse Distributors*
United States Steel Export Company, New York

UNITED STATES STEEL

Professional Engineering Directory

BLACK & VEATCH
Consulting Engineers
Water, Steam and Electric Power Investigations, Design, Supervision of Construction, Valuation and Tests
4706 Broadway KANSAS CITY, MO.

SANDERSON & PORTER
ENGINEERS
FINANCING—REORGANIZATION—DESIGN—CONSTRUCTION
of
INDUSTRIALS and PUBLIC UTILITIES
Chicago New York San Francisco

E. T. L.
TESTS
Electrical, Chemical, Mechanical, Photometric
INSPECTIONS — Materials and Supplies
RESEARCH — Private Labs. for Clients
Electrical Testing Laboratories
New York, N. Y.

SARGENT & LUNDY
ENGINEERS
140 South Dearborn Street
CHICAGO, ILLINOIS

FRANK F. FOWLE & CO.
Electrical and Mechanical Engineers
35 East Wacker Drive CHICAGO

A. Y. TAYLOR & COMPANY
Municipal and Industrial Consulting Engineers
Reports, Appraisals, Design
Supervision of Construction
2 So. Central Ave. Clayton, Mo.

JACKSON & MORELAND
Engineers
Public Utilities—Industrials
Railroad Electrification
Designs and Supervision—Valuations
Economic and Operating Reports
BOSTON NEW YORK

HOWARD S. WARREN
Consulting Electrical Engineer
420 Lexington Ave. NEW YORK

HAROLD J. McCREARY
Mem. A.I.E.E. & W.S.E.
Consulting Engineer
Laboratory Facilities
Research, Development, Design, Factory Practice, Patent Studies
Electronics, Television, Radio, Railroad Signaling, Telephony
106 W. Adams St. Phone STAte 4003 Chicago

THE J. G. WHITE Engineering Corporation
Engineers—Constructors
Oil Refineries and Pipe Lines, Steam and Water Power Plants, Transmission Systems, Hotels, Apartments, Offices and Industrial Buildings, Railroads
80 BROAD STREET NEW YORK

Professional services over a wide range are offered by these cardholders.

Consult the directory when in need of specialized engineering advice.

J. W. WOPAT
Consulting Engineer
TELEPHONE ENGINEERING
Construction Supervision
Appraisals—Financial
Rate Investigations
1510 Lincoln Bank Tower, Ft. Wayne, Ind.

Z. H. POLACHEK
Reg. Patent Attorney
Professional Engineer
PATENT—TRADE MARK SPECIALIST
Individual or Yearly Basis
1234 Broadway (At 31 St.) NEW YORK
Phone Longacre 5-3088

J. G. WRAY & CO.
Engineers
Utilities and Industrial Properties
Appraisals, Plans, Financial Investigations, Construction Organizations, Rate Surveys, Estimates, Management
105 West Adams St., Chicago

Employment Bulletin

Engineering Societies Personnel Service, Inc.

MAINTAINED for their members by the national societies of civil, mining, mechanical, and electrical engineers, in co-operation with other organizations. An inquiry to any of the four offices will bring full information.

A weekly bulletin of engineering positions open is available to members of the co-operating societies at a subscription of $3 per quarter or $10 per annum, payable in advance.

In the interest of effective service, it is essential that members using the employment service keep the bureau office serving them advised at reasonable intervals concerning their availability for employment, concerning any change in status, and immediately upon acceptance of any employment.

Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York office.

Men Available

PROF ENGR, member AIEE; 41, family; 18 yrs domestic and foreign exper commercial and indus engg in largest indus concern, also production studies; excellent references. Desires pos of greater responsibility. E-834.

RADIO AND ELEC ENGR; M.S.; 8 yrs exper in electronics, radio and ultra high frequency, with inventions of proven value, desires pos in research, des and mfg. Available most locations. E-835.

EXEC ENGR; Business Administration grad; age, 39. Exper includes costs, budgets, statistics, procedures, economic studies, safety, claims, insurance, labor relations, personnel administration. Supervision, research, reports. Location, New York. E-836.

EVENING ELEC ENGG STUDENT desires pos in the elec field, preferably com, as a draftsman, test man or tech assistant. Progress in col very good; most tech subjects completed. E-837.

MANAGER, DESIGNER, 10 yrs; distr, pwr transf, induction voltage regulators; 40, married; desires connection with transf mfr, pwr co. 10 yrs maintenance, repairs, rotating machy, controls. Location, Ohio, vicinity. E-838.

EMPL DIRECTOR, Personnel Director or Empl Manager; 32, married. 5 yrs exper in a responsible public personnel pos. Grad Rensselaer Polytechnic Inst, E.E. degree. Location immaterial. E-839-415-C-1-San Francisco.

E.E., B.S.; grad work in Com, M.I.T., 1933; 7 yrs exper in mfg, devpmt, des, of radio receivers and components. Test and inspec methods, eqpt des, quality control, plant layout. Employed. E-840.

E.E.; 22 yrs des, supervision pwr stations, substations, switch structures, distr, investigations, economic studies, indus plants switchboards, transf stations, pwr, ltg, control, interlocking and signal systems. E-841.

E.E., univ grad; about 20 yrs exper, mostly in pwr prod and distr, desires pos preferably with large user of elec pwr or with pub util organization E-842.

REGISTERED PROF E.E.; 39, married; 10 yrs exper maintenance engr of mech and elec eqpt in mfg plants and office bldgs. Desires pos as eqpt engr, supervision of sales. Metropolitan area preferred. E-843.

ENGR with long indus exper and specialized knowledge and exper in U. S. and foreign patents seeks connection requiring expert liaison between inventors and attorneys in radio or allied fields. E-844.

B.E.E.; 30, married; 3 yrs elec des; 4 yrs electronics research and devpmt, including indus control. Excellent exper and record. Prefer East. E-845.

GRAD E.E., degree; license: civil service rating. 20 yrs des, specifications, estimating, correspondence, inspec, supervision, wiring public, private, indus bldgs various types, sub-stations, transm lines. Executive ability, full responsibility. E-846.

AIEE, ASSOCIATE; 39; 20 yrs tel plant. 16 yrs specializing automatic switching, electronics, remote control. Indus com systems, large and small, domestic and foreign. Available immed. East preferred. E-847.

B.S.E.E., Lehigh Univ; 29, married; desires pos valuation or elec pwr sales and distr; 5 yrs engg exper; now employed. Desires pos with future. Location immaterial. E-848.

AIEE member; 45, married; 21 yrs with present pub util and its predecessors in supervisory and exec capacity, desires permanent pos with util or indus organization as oprn and/or maintenance engr. Now employed. E-849.

ENGINEERING SOCIETIES PERSONNEL SERVICE, INC.

NEW YORK 31 W. 39th St.
SAN FRANCISCO 57 Post St.
CHICAGO 211 W. Wacker Dr.
DETROIT 272 Hotel Statler

A.C. & D.C. • A.C. & D.C.

The Only one for measuring both A.C. and D.C.

That's right, there is only one clamp-type ammeter which measures both A. C. and D. C.—the double-duty TONG TEST. Do your current measuring in less time, with one instrument and save the difference.

TONG TEST is accurate and absolutely safe; it measures currents up to 800 amperes without breaking the circuit and weighs only 2¾ pounds. Low in price, but precision-built, a 2-in-1 TONG TEST quickly pays for itself. All sizes are available from stock.

For complete facts about the TONG TEST, send for the TONG TEST bulletin, today.

Columbia Electric Mfg. Co.
4525 Hamilton Ave. Cleveland, O.

A.C. & D.C. • A.C. & D.C. • A.C. & D.C. • A.C. & D.C.

TONG TEST

THE ONLY CLAMP-TYPE A. C. & D. C. AMMETER

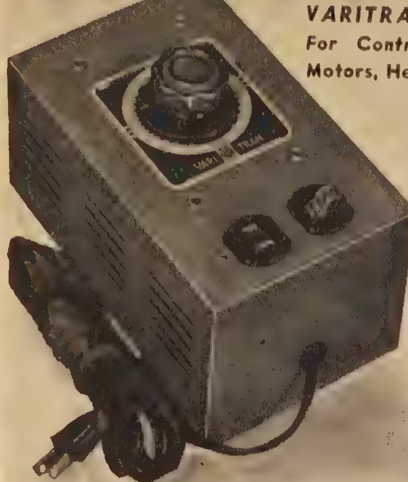
A.C. & D.C.

VARIABLE VOLTAGE

For Your Laboratory, Your Product, or Your Production Line

UTC

VARITRAN



VARITRAN CONTROL UNITS

For Controlling: Rectifier Output, Motors, Heaters, Lights, Line Voltage

The UTC Varitran employs a non-fusing graphite roller riding over the transformer turns to effect a transformer providing continuously variable output voltage. Regulation, efficiency, and distortion characteristics are excellent. Standard 115 V. input (0-130 V. output). Units are available in 2, 5, 7.5, 11, 17, 30, and 44 Amp. sizes. Write for Bulletin PS-404.

★ Smooth Control ★ Excellent Regulation ★ High Efficiency
★ Rugged Construction ★ Wide Range (0-130 V.)
★ Low Temperature Rise ★ Roller Contact ★ No Distortion

UNITED TRANSFORMER CORP.

150 VARICK STREET ★ NEW YORK, N. Y.

EXPORT DIVISION: 100 VARICK STREET NEW YORK, N. Y. CABLES: "ARLAB"

Science Abstracts

All electrical engineers actively engaged in the practice of their profession should subscribe to "Science Abstracts."

Published monthly by the Institution of Electrical Engineers, London, in association with the Physical Society of London, and with the cooperation of the American Institute of Electrical Engineers, the American Physical Society and the American Electrochemical Society, they constitute an invaluable reference library.

Through "Science Abstracts" engineers are enabled to keep in touch with engineering progress throughout the world, as one hundred and sixty publications, in various languages, are regularly searched and abstracted. "Science Abstracts" are published in two sections, as follows:

"A"—PHYSICS—deals with electricity, magnetism, light, heat, sound, astronomy, chemical physics.

"B"—ELECTRICAL ENGINEERING—deals with electrical plant, power transmission, traction, lighting, telegraphy, telephony, wireless telegraphy, prime movers, engineering materials, electrochemistry.

Through special arrangement, members of the A.I.E.E. may subscribe to "Science Abstracts" at the reduced rate of $5.00 for each section, and $10.00 for both. Rates to non-members are $9.00 for each section and $15.00 for both. Subscriptions should start with the January issue. The first volume was issued in 1898. Back numbers are available, and further information regarding these can be obtained upon application to P. F. Rowell, Secy., I.E.E., Savoy Place. Victoria Embankment, London, W. C. 2, England.

AIEE

American Institute of Electrical Engineers
33 West 39th Street, New York

OHMITE

All-Ceramic High Current TAP SWITCHES

★ Slow-Break ★ Quick-Make Action ★ Specially Designed For A. C. Use ★

★ Compact, all-enclosed, perfectly insulated. Silver-to-silver contacts. Available in 10, 15, 25, 50 and 100 ampere sizes with any number of taps up to 11, 12, 12, 12 and 8 respectively. Also available in tandem assemblies to form multi-pole switches.

Write on company letterhead for Catalog No. 40

Ohmite Manufacturing Co., 4803 Flournoy St., Chicago, U. S. A.

Be Right with OHMITE

RHEOSTATS • RESISTORS • TAP SWITCHES

Advertised Products Index

AMMETER COMPENSATING COILS
Minerallac Electric Co., Chicago

AMMETERS, VOLTMETERS
(See INSTRUMENTS, ELECTRICAL)

BRUSHES, COMMUTATOR
National Carbon Co., Inc., Cleveland, O.

BUS BAR SUPPORTS
Burndy Engg. Co., Inc., New York
General Electric Co., Schenectady, N. Y.

CABLE ACCESSORIES
General Electric Co., Schenectady, N. Y.
Minerallac Electric Co., Chicago

CAPACITORS
Behr, Leo, Philadelphia, Pa.
General Electric Co., Schenectady, N. Y.
Solar Mfg. Corp., Bayonne, N. J.
Westinghouse E. & M. Co., E. Pittsburgh

CIRCUIT BREAKERS

Air Enclosed
General Electric Co., Schenectady, N. Y.
I-T-E Circuit Breaker Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.
Westinghouse E. & M. Co., E. Pittsburgh

Oil
Allis-Chalmers Mfg. Co. Milwaukee, Wis.
General Electric Co., Schenectady, N. Y.
Roller-Smith Co., Bethlehem, Pa.
Westinghouse E. & M. Co., E. Pittsburgh

CONDENSERS, ELECTROSTATIC
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
Solar Mfg. Corp., Bayonne N. J.
Westinghouse E. & M. Co., E. Pittsburgh

CONDUIT PRODUCTS
General Electric Co., Bridgeport, Conn.
National Elec. Products Corp., Pittsburgh

CONNECTORS, SOLDERLESS
Burndy Engg. Co., Inc., New York
General Electric Co., Schenectady, N. Y.
Krueger & Hudepohl, Cincinnati, Ohio
National Elec. Products Corp., Pittsburgh

CONTROLLERS
Allis-Chalmers Mfg. Co., Milwaukee, Wis.
General Electric Co., Schenectady, N. Y.
Rowan Controller Co., Baltimore, Md.
Westinghouse E. & M. Co., E. Pittsburgh

CONVERTERS, SYNCHRONOUS
Allis-Chalmers Mfg. Co., Milwaukee, Wis.
General Electric Co., Schenectady, N. Y.
Westinghouse E. & M. Co., E. Pittsburgh

CORPRENE GASKETS & PACKINGS
Armstrong Cork Co., Lancaster, Pa.

DRAFTING PENCILS
Dixon Crucible Co., J., Jersey City, N. J.

ELECTRONIC TUBES
General Electric Co., Schenectady, N.Y.
Westinghouse E. & M. Co., E. Pittsburgh

FIBERGLAS INSULATION
Owens-Corning Fiberglas Corp., Toledo, O.

FURNACES, ELECTRIC
American Bridge Co., Pittsburgh
General Electric Co., Schenectady, N. Y.

GASKETS, "CORPRENE"
Armstrong Cork Co., Lancaster, Pa.

GENERATORS AND MOTORS
Allis-Chalmers Mfg. Co., Milwaukee, Wis.
General Electric Co., Schenectady, N. Y.
Westinghouse E. & M. Co., E. Pittsburgh

GROUND RODS
Copperweld Steel Co., Glassport, Pa.

HEATING UNITS
General Electric Co., Schenectady, N. Y.

INSTRUMENTS, ELECTRICAL

Graphic
Ferranti Electric, Inc., New York
General Electric Co., Schenectady, N. Y.
Leeds & Northrup Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.
Westinghouse E. & M. Co., E. Pittsburgh
Weston Elec. Instrument Corp., Newark, N.J.

INSTRUMENTS, ELECTRICAL (Con't)

Indicating
Ferranti Electric, Inc., New York
General Electric Co., Schenectady, N. Y.
Leeds & Northrup Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.
Shallcross Mfg. Co., Collingdale, Pa.
Westinghouse E. & M. Co., E. Pittsburgh
Weston Elec. Instrument Corp., Newark, N.J.

Integrating
Ferranti Electric, Inc., New York
General Electric Co., Schenectady, N. Y.
Shallcross Mfg. Co., Collingdale, Pa.
Westinghouse E. & M. Co., E. Pittsburgh
Weston Elec. Instrument Corp., Newark, N.J.

Scientific Laboratory, Testing
Acme Elec. & Mfg. Co., Cuba, N. Y.
Du Mont Labs., Inc., Allen B., Passaic, N. J.
Ferranti Electric Inc., New York
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
Leeds & Northrup Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.
Shallcross Mfg. Co., Collingdale, Pa.
Westinghouse E. & M. Co., E. Pittsburgh
Weston Elec. Instrument Corp., Newark, N.J.

INSULATING MATERIALS

Cloth
General Electric Co., Bridgeport, Conn.
Irvington Varnish&Ins. Co., Irvington, N. J
Minerallac Electric Co., Chicago
Westinghouse E. & M. Co., E. Pittsburgh

Compounds
General Electric Co., Bridgeport, Conn.
Minerallac Electric Co., Chicago.
Roebling's Sons Co., John A., Trenton, N. J.
Westinghouse E. & M. Co., E. Pittsburgh

Fiberglas
Owens-Corning Fiberglas Corp., Toledo, O.

Moulded
General Electric Co., Bridgeport, Conn.
Westinghouse E. & M. Co., E. Pittsburgh

Paper
General Electric Co., Bridgeport, Conn.
Irvington Varnish & Ins. Co., Irvington, N.J.
Westinghouse E. & M. Co., E. Pittsburgh

Tape, Friction
Minerallac Electric Co., Chicago
Okonite Company, The, Passaic, N. J.
Roebling's Son Co., John A., Trenton, N. J.

Varnishes
General Electric Co., Bridgeport, Conn.
Irvington Varnish & Ins. Co., Irvington, N. J.
Minerallac Electric Co., Chicago

INSULATORS, GLASS
Corning Glass Works, Corning, N. Y.

INSULATORS, PORCELAIN
General Electric Co., Schenectady, N. Y.
Lapp Insulator Co., LeRoy, N. Y.
National Elec. Products Corp., Pittsburgh
Ohio Brass Co., Mansfield, O.
Universal Clay Products Co., Inc., Sandusky, O.
Westinghouse E. & M. Co., E. Pittsburgh

INSULATOR TESTING EQUIPMENT
Ferranti Electric, Inc., New York
General Radio Co., Cambridge, Mass.
Roller-Smith Co., Bethlehem, Pa.

LIGHTING EQUIPMENT, OUTDOOR
General Electric Co., Schenectady, N. Y.
Westinghouse E. & M. Co., E. Pittsburgh

LIGHTNING ARRESTERS
General Electric Co., Schenectady, N. Y.
Westinghouse E. & M. Co., E. Pittsburgh

LOAD RECORDERS—CONTROLLERS
Leeds & Northrup Co., Philadelphia

METERS, ELECTRICAL
(See INSTRUMENTS, ELECTRICAL)

MOTORS
(See GENERATORS AND MOTORS)

OSCILLOGRAPHS, CATHODE RAY
Du Mont Labs. Inc., Allen B., Passaic, N. J.
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
Westinghouse E. & M. Co., E. Pittsburgh

PENCILS, DRAWING
Dixon Crucible Co., J., Jersey City, N. J.

POLE LINE HARDWARE
Ohio Brass Co., Mansfield, O.

PORCELAIN, ELECTRIC
Universal Clay Products Co., Inc., Sandusky, O.

RECTIFIERS
Allis-Chalmers Mfg. Co., Milwaukee, Wis.
General Electric Co., Schenectady, N. Y.
International Tel. Dev. Co., Inc., New York
Westinghouse E. & M. Co., E. Pittsburgh

REGULATORS, VOLTAGE
Allis-Chalmers Mfg. Co., Milwaukee, Wis.
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
Roller-Smith Co., Bethlehem, Pa.
Sola Electric Co. Chicago, Ill.
Westinghouse E. & M. Co., E. Pittsburgh

RELAYS
General Electric Co., Schenectady, N. Y.
I-T-E Circuit Breaker Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.
Weston Elec. Instrument Corp., Newark, N. J.
Westinghouse E. & M. Co., E. Pittsburgh

RESISTORS
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
International Resistance Co., Philadelphia
Ohmite Mfg. Co., Chicago
Shallcross Mfg. Co., Collingdale, Pa.
Westinghouse E. & M. Co., E. Pittsburgh

RHEOSTATS, LABORATORY
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
International Resistance Co., Philadelphia
Ohmite Mfg. Co., Chicago
Westinghouse E. & M. Co., E. Pittsburgh

STEEL, ELECTRICAL
Carnegie-Illinois Steel Corp., Pittsburgh

SWITCHBOARDS
Allis-Chalmers Mfg. Co., Milwaukee, Wis.
General Electric Co., Schenectady, N. Y.
I-T-E Circuit Breaker Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.
Westinghouse E. & M. Co., E. Pittsburgh

SWITCHES, AUTOMATIC TIME
General Electric Co., Schenectady, N. Y.
Minerallac Electric Co., Chicago

SWITCHES, DISCONNECT
General Electric Co., Schenectady, N. Y.
Roller-Smith Co., Bethlehem, Pa.
Westinghouse E. & M. Co., E. Pittsburgh

SWITCHES, GENERATOR FIELD
I-T-E Circuit Breaker Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.

TOWERS, TRANSMISSION
American Bridge Co., Pittsburgh

TRANSFORMERS
Acme Elec. & Mfg. Co., Cuba, N. Y.
Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Ferranti Electric, Inc., New York
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
Kuhlman Electric Co., Bay City, Mich.
Roller-Smith Co., Bethlehem, Pa.
Sola Electric Co., Chicago
United Transformer Corp., New York
Westinghouse E. & M. Co., E. Pittsburgh

TURBINES and TURBINE GENERATORS
Allis-Chalmers Mfg. Co., Milwaukee, Wis.
General Electric Co., Schenectady, N. Y.
Westinghouse E. & M. Co., E. Pittsburgh

VARNISHES, INSULATING
General Electric Co., Bridgeport, Conn.
Irvington Varnish & Ins. Co., Irvington N. J.
Westinghouse E. & M. Co., E. Pittsburgh

WELDERS, ARC
General Electric Co., Schenectady, N. Y.
Westinghouse E. & M. Co., E. Pittsburgh

WELDING WIRE
American Steel & Wire Co., Cleveland, O.
General Electric Co., Schenectady, N. Y.
Roebling's Sons Co., John A., Trenton, N. J.

WIRES AND CABLES
Aluminum Co. of America, Pittsburgh
American Steel & Wire Co., Cleveland, O.
Belden Mfg. Co., Chicago
Copperweld Steel Co., Glassport, Pa.
Crescent Ins. Wire & Cable Co., Trenton, N.J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Kerite Ins. Wire & Cable Co., New York
National Elec. Products Corp., Pittsburgh
Okonite Company, The, Passaic, N. J.
Okonite-Callender Cable Co., Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.

"I judge the telephone company by the people who work for it"

A little while ago a Vermont newspaper editor, John Hooper, commented on the telephone company and its people. His words express so well the ideals toward which we are striving that we quote them here.

"I don't know how big the telephone company is, but it is big enough to exceed my mental grasp of business.

"But I don't find myself thinking of it as a business, even in my day-to-day contacts. Rather, my attention is on the voice that says, 'Number, please.' I find myself wondering if that voice is feeling as well as it always seems to, or if it feels just as hot and weary as I do, and would say so if it wasn't the kind of voice it is.

"The first time the business angle really struck home was when I read that my friend Carl had completed thirty years with the company.

"Now it happens that I know something of the details of those thirty years with the company, and I believe they are a credit both to Carl and to the big business for which he works.

"In 1907 Carl was a high school boy confronted with the need for earning money in his spare time. He happened to get a job as Saturday night operator in the telephone exchange. He worked at this job for three years and then entered the university.

"While in college he did some substituting at the exchange in his home town in vacations. After graduation, he was hired full time by the telephone company, not in an 'executive' position which some folks think goes with a college diploma, but as a lineman.

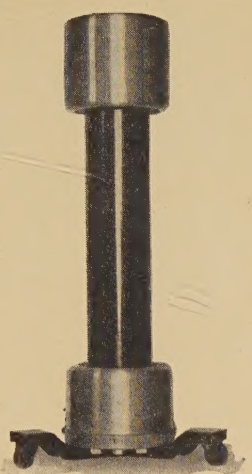
"Within a year he was made wire chief of the district, a job which he held for the next ten years. He was then transferred to a larger city as manager of the office. Then he was promoted to sales manager of the division.

"A year later he was sent to another State, as district manager. In less than a year after this appointment, he was made manager for the entire State.

"I don't know much about the telephone company as a business; I can only judge it by the people who work for it. Just where the dividing line is between a business and the people who work for it, I don't know. I don't think there is any line."

Bell Telephone System

"THE TELEPHONE HOUR" IS BROADCAST EVERY MONDAY. (N. B. C. RED NETWORK, 8 P. M., EASTERN DAYLIGHT SAVING TIME.)

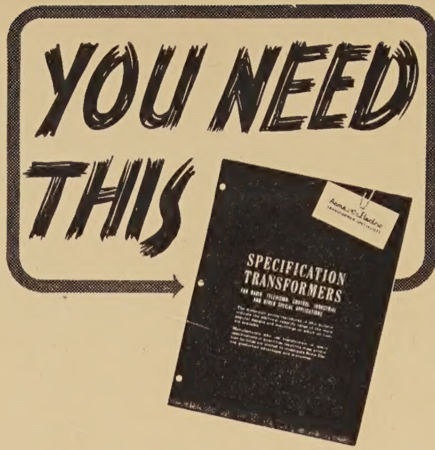


STANDARD CAPACITOR

Carefully shielded, primary standard of zero power factor, compressed-gas dielectric, for use at high voltage and power frequencies.

Detailed description available on request

LEO BEHR 12 Harvey St. PHILADELPHIA



Every electrical engineer should have this ready reference bulletin of Specification Transformers. It is intended to simplify your design work. It is informative and complete. Write for copy of Specification Transformer Bulletin 155 to-day.

P. S. If you've a special-design transformer problem, don't waste time—call an Acme transformer engineer and let transformer specialists assist you in building better equipment.

The ACME ELECTRIC & MFG. CO.
22 WATER ST. CUBA, N. Y.

Acme Electric TRANSFORMERS

RECOMMENDED PRACTISE FOR

Electrical Installations on Shipboard

(MARINE RULES)

Sec. No. 45
AIEE Standards
With Addenda as of March 1941

THE latest edition "of Recommended Practise for Electrical Installations on Shipboard" (Marine Rules) is published as Section 45 of the AIEE Standards. The pamphlet contains 100 pages; price is $1.50 (50% discount to members of the AIEE).

These rules have been drawn up to serve as a guide for the equipment of merchant ships with electrical apparatus for lighting, signaling, communication, power and propulsion for both alternating and direct current systems. They indicate what is considered good engineering practise with reference to safety of the personnel and of the ship itself, as well as reliability and durability of the electrical apparatus.

American Institute of Electrical Engineers

33 West Thirty-Ninth Street, New York

ADVERTISERS

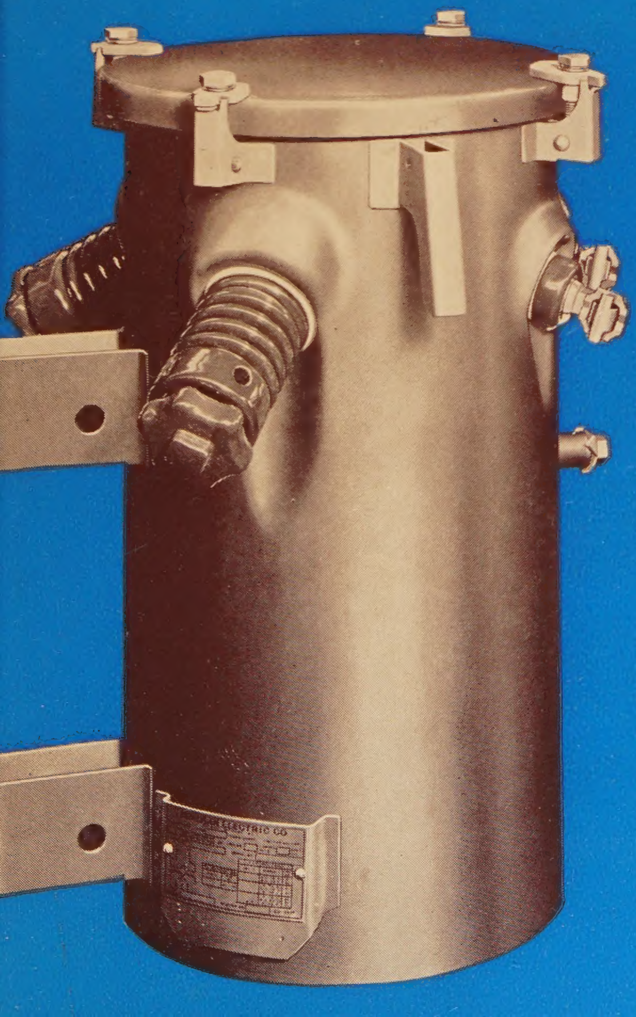
** See previous issues.*

Kuhlman Transformers

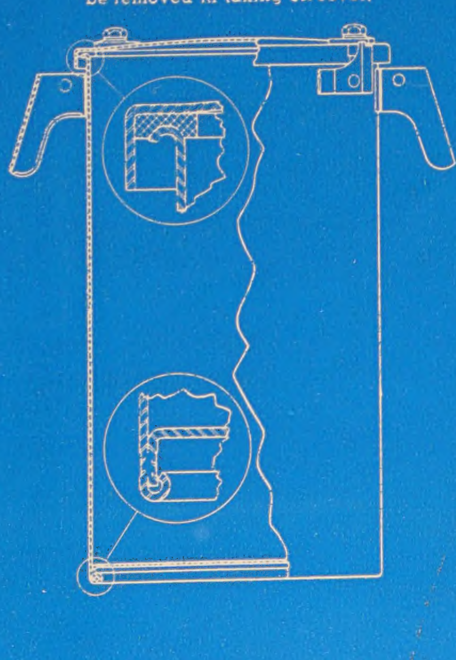
DESIGNED AND BUILT FOR LOWER MAINTENANCE AND LONGER LIFE . .

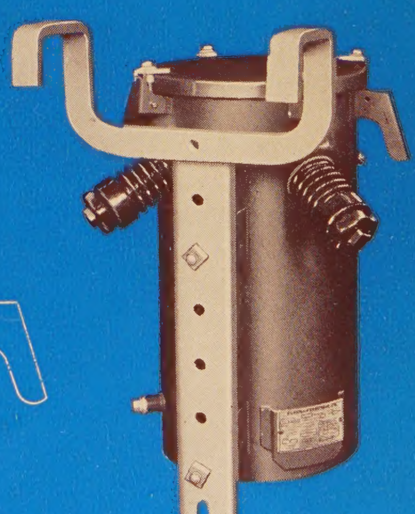
Utility maintenance men these days appreciate the importance of good construction in transformer tanks. For that reason no bet is overlooked in the construction of Kuhlman Transformer tanks. The entire tank and body is formed from copper bearing steel. The top edge is rolled to form a perfect gasket seat. The bottom is seam-welded and rolled to form a heavily reinforced base. Cover clamps are forged and machined from bronze—no part need be removed in taking off the cover. The lifting lugs greatly facilitate handling. The rigid steel cover banishes any danger of cover breakage. The pockets for the primary and secondary bushings are pressed directly into the tank body which not only eliminates welding, but the recesses provide ideal protection for the bushing gaskets. Perhaps the most important feature of Kuhlman tanks from the maintenance standpoint is the Porcelain enamel finish which guards the tank against the havoc of rust and corrosion. The T cross arm hanger, the direct pole mounting brackets, position of grounding studs and nameplate on Kuhlman tanks now conform to the new E. E. I. — NEMA standards.

For more complete facts about the advantages of Kuhlman Distribution or Power transformers write to **KUHLMAN ELECTRIC COMPANY, BAY CITY, MICHIGAN.**



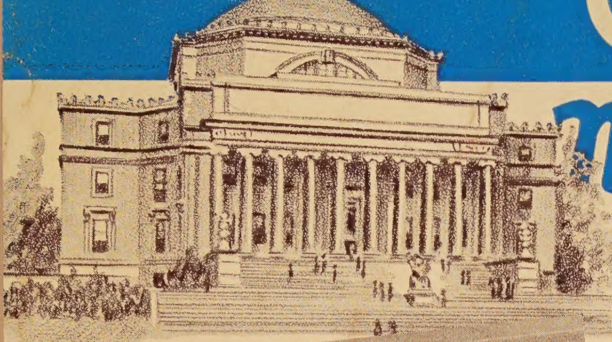
(Below) Drawing showing construction of tank and top and bottom seams. Note how rolling at base increases strength — and how rolling at top provides perfect seat for gasket. Bronze cover clamps need not be removed in taking off cover.





(Above) Photograph showing detail of new E. E. I.—NEMA standard T cross arm hanger. Kicker bracket (not shown) is available. In every conceivable way Kuhlman transformer tanks are designed and built to assure lower maintenance and longer life.

THE LARGE FIELD COILS IN COLUMBIA'S *new* CYCLOTRON (ATOM SMASHER) WERE BUILT BY Murray

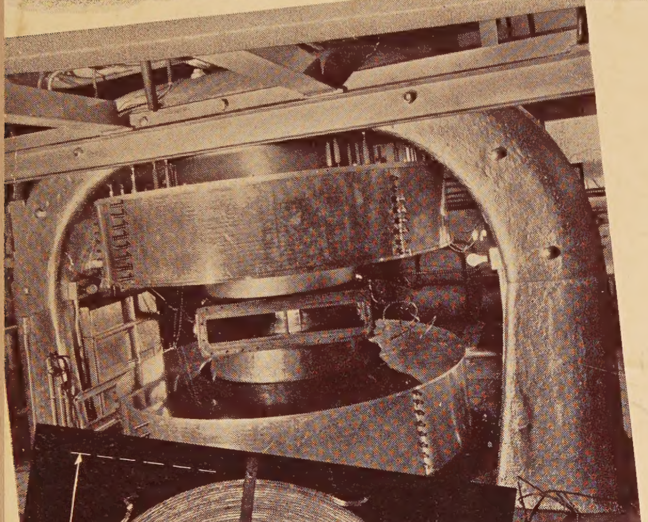


Of the several Cyclotrons recently installed by leading universities the newest—and one of the largest and most interesting—is Columbia's. The Murray Organization (Metropolitan Device Corporation) was chosen to provide the 16 copper field coils and the 16 water cooling coils for this instrument.

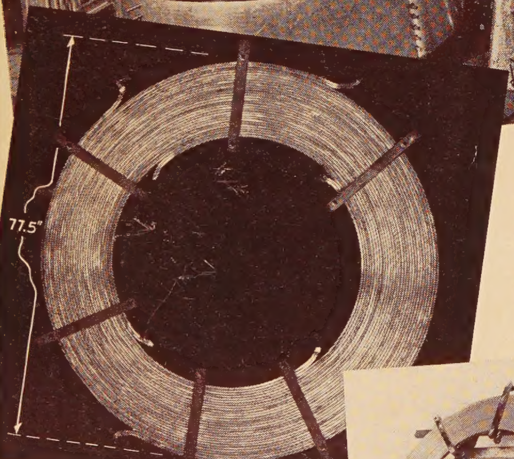
Valuable additional physical data on the structure, behavior and transmutation of atoms is expected from the use of this exceedingly large and powerful apparatus. The pictures and data on this page, for which we are indebted to Dr. Pegram, Dr. Mitchell, Dr. Dunning and Dr. Booth of Columbia's Pupin Physics Laboratory, the designers and builders of this latest Cyclotron—are published for the information of all electrical engineers. Metropolitan Device Corp., Brooklyn, N. Y.

THE TECHNICAL FACTS

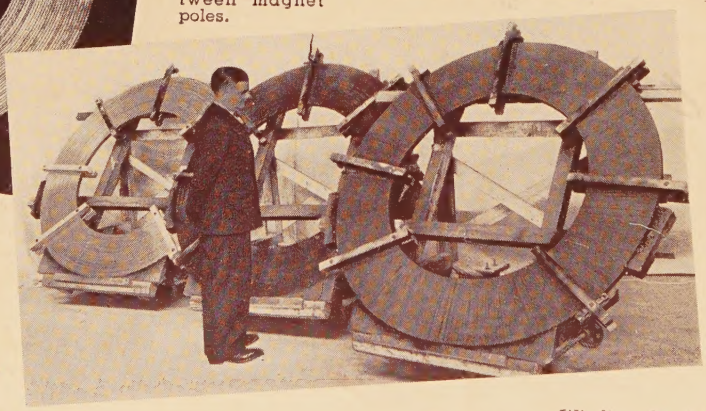
For the interesting electrical data on this CYCLOTRON *just mail the coupon*



General view of Cyclotron showing magnet, aluminum shielded field and water cooling coils and accelerating chamber between magnet poles.



Six foot five and one-half inch rectangular cooling coil.



Field coils in 3 stages of manufacture — left, wound; center, wound and taped; right, and treated.

Winding the field coils—close-up of .1" x 1½" flat copper separated by fibroid insulation.

METROPOLITAN DEVICE CORP'N
Brooklyn, N. Y.

Please send me data on Columbia's CYCLOTRON.

NAME________________ TITLE________________

COMPANY________________

ADDRESS________________

Made by the makers of Murray

Bridging Shells • Cable Racks • Cable Grips • Current Limiting Reactors • Disconnect Plugs • Gas Cock Seals • Malleable Strapping • Meter Boxes • Meter & Entrance Switches • Meter Seals • Meter Testing Devices • Meter Troughs • Panelboxes • Range Switches • Safety Switches • Solderless Connectors • Street Light Servicing Ladder.